Proceedings of 2004 IEEE/RSJ International Conference on
Intelligent Robots and Systems
September 28 - October 2, 2004, Sendai, Japan

Modular ATRON: Modules for a self-reconfigurable robot

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***Abstract*— This paper describes the mechanical and electrical design of a new lattice based self-reconfigurable robot, called the ATRON. The ATRON system consists of several fully self-contained robot modules, each having their own processing power, power supply, sensors and actuators. The ATRON modules are roughly spheres with equatorial rotation. Each module can be connected to up to eight neighbors through four male and four female connectors. In this paper, we describe the realization of the design, both the mechanics and the electronics. Details on power sharing and power consumption is given. Finally, this paper includes a brief outline of our future work on the ATRON system.**

I. Introduction

A self-reconfigurable robot is a machine built from several atomic modules, that by rearranging their position with respect to each other, can change the shape and functionality of the entire machine or organism. Robots capable of performing self-reconfiguration may eventually be used in, say, a production line having a self-reconfigurable robot packaging goods one day, and sorting objects on an assembly line the next day without the need for human intervention between the two tasks. Other applications of a self-reconfigurable robot could be cleaning or maintaining hazardous machinery and environments where humans cannot go or performing searches in collapsed buildings or shafts. However building and controlling such robots is still a subject to research, and by designing, testing and producing a robotic module forming the basic building block in a self-reconfigurable robot, we hope to build a fully autonomously, self-contained reconfigurable robot. This robot will then found the basis as a tool for further researching in distributed control, self-reconfiguration algorithms and scientific engineering.

In particular, we expect to build towards 100 modules and have them perform autonomous reconfiguration in 3D, thus facing new challenges in the field of self - reconfiguration. Therefore it is crucial that our proposed robotic module is: Cheap to allow mass production; flexible to allow a wide range of experiments and setups to be investigated; and truly self-contained to allow the robot to reconfigure without the interference of power lines and communication cables.

II. Related work

In this section two other self-reconfigurable robots will be addressed: The CONRO[1] and the M-TRAN[2]. The CONRO and the M-TRAN have been chosen as examples of other researchers work, because we in the ATRON would like to combine some interesting properties from both systems. We would like our robotic module to offer both a “yaw” and a “pitch” actuation as the CONRO but at the same time we would like a robotic module that reconfigures as easily as the M-TRAN modules and works in a lattice structure.

The CONRO self-reconfigurable robot was first presented by Will et al.[1] and further described in [2]. It is a chain type robot developed at University of Southern California, USA. A CONRO robotic module consists of a cubic passive connector and an active connecting plate that can connect onto three of the surfaces of the passive connector. The two connectors are held together by two joints allowing the connectors to “yaw” and “pitch” with respect to each other. Using this approach a number of CONRO modules may form snakes, six-legged walkers, snake-wheels and many other structures. However, being a chain structure where the joint positions are not discretized, it is difficult to make CONRO modules connect, or “dock” (as described by Will and Shen in [3]).

The M-TRAN [4], [5] has currently reached generation 2, with the M-TRAN II modules and is being developed and maintained at AIST Tsukuba, Japan. The M-TRAN module has a passive end and an active end connected by a link. Both the passive and the active end are semicylindres able to rotate 180° around the center of the cylinder. While this seems very similar to the CONRO modules, the M-TRAN modules differs from the CONRO modules by missing the yaw actuation, and by being designed to operate in a discretized lattice. Being designed to work in a lattice, the M-TRAN needs not to worry about the positioning of modules when connecting. On the other hand, missing the yaw actuation an M-TRAN organism where all modules are aligned in the same orientation will never be able to change orientation.

Although this section has focused on the M-TRAN and the CONRO modules as examples, several other groups,

[1]CONfigurable RObots
[2]Modular TRANsformer

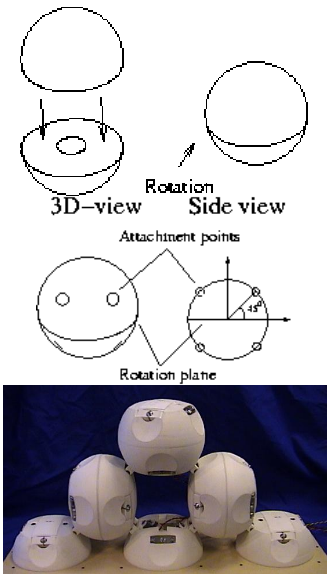

Fig. 1. **Top:** Idea behind the basic design. Two half spheres joint together by an actuated rotation mechanism able to rotate as many revolutions as desired in both directions (for possible use as wheels). **Middle:** Placement of the attachment points at $45°$ latitude and with an even longitudinal distribution of $90°$. **Bottom:** Picture of three prototype-0 ATRONs on a testing board.

have proposed their approach towards a self-reconfigurable robot. These approaches includes the Telecubes by Yim et. al [6], [7] from Palo Alto, the I-Cubes [8] from Carnegie Mellon University by Ünsal, Kýlýççöte and Khosla, the PolyBots [9] also from Palo Alto and Rus and Vona's Crystalline [10], [11] from Dartmouth (see also the survey of self-reconfigurable robots [12], 2001.)

III. The ATRON design idea

As part of our research in self-reconfigurable robots, we are currently developing a prototype homogeneous unit modular self-reconfigurable robot system called ATRON (shown in figure 1). ATRON is a lattice-based system, in which modules are arranged in a subset of a surface-centered cubic lattice. In this lattice, modules are placed so that their rotation axis is parallel to the x, y or z axis. Modules are placed so that two connected modules have perpendicular rotation axes. The basic motion primitive for ATRONs is a $90°$ rotation around the equator, while one hemisphere is rigidly attached to one or two other modules and the other hemisphere is rigidly attached to the main part of the structure. This will cause the attached module(s) to be rotated around the rotation axis of the active module.

This design is a compromise between many mechanical, electronic and control considerations. Connectors in the ATRON system use a male-female design for mechanical reasons. The connectors are arranged so that every second connector on a hemisphere is male, every second is female.

In order to realize self-reconfiguration with the ATRON system, we require a module to:

- Be able to connect and disconnect with its neighbors.
- Have neighbor to neighbor communication.
- Be able to sense the state of its connectors.
- Sense the relative rotation of its two hemispheres.

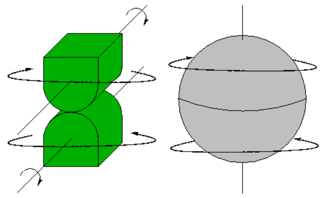

Fig. 2. How the idea of a rotating link in an M-TRAN corresponds to an ATRON module.

- Perform $360°$ rotation around the equator.

IV. The ATRON hardware realization

A. Mechanical design

Like the M-TRAN module, the ATRON has two "parts" connected by an actuated joint. Where the M-TRAN is actuated around two parallel axes, the ATRON is actuated around the axis perpendicular to the equatorial plane, as illustrated in figure 2.

The ATRON module, shown in figure 3, is built mainly from aluminum with some brass (gearing for the center motor) and steel (passive connectors and needle bearing in the center).

The rest of this section will in details describe several aspects of the mechanical design, which was mainly developed by Kristian Kassow and Richard Beck.

B. Center design

As stated in section III the self-reconfiguration will be realized by having a module connect to its neighbor, rotate a multiple of $90°$, let the rotated module connect to a new neighbor and release the initial connection. Hence reconfiguration will involve a lot of rotation around modules equator and internal wiring of the module will get twisted by these rotations, unless care is taken. Keeping track of revolutions will be a cumbersome — but necessary — task if power lines and feedback for actuators should be passed through equator by wires. As we will describe in section IV-C.2 a result of this challenge was to put processing power in both hemispheres. To transfer power and data from one hemisphere to another, a slip ring was built into the hemispheres parallel to equator, as illustrated in figure 4.

This design of the center 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 means that an ATRON module is able to detect if the hemispheres are rotating without they are intended to do so, thus offering a possibility to correct for external disturbances.

1) Cutoffs: Although the initial design was two hemispheres as illustrated in figure 2, the actual modules are composed by two four-sided pyramids with carvings to allow rotation within an organism. Figure 5 illustrates that

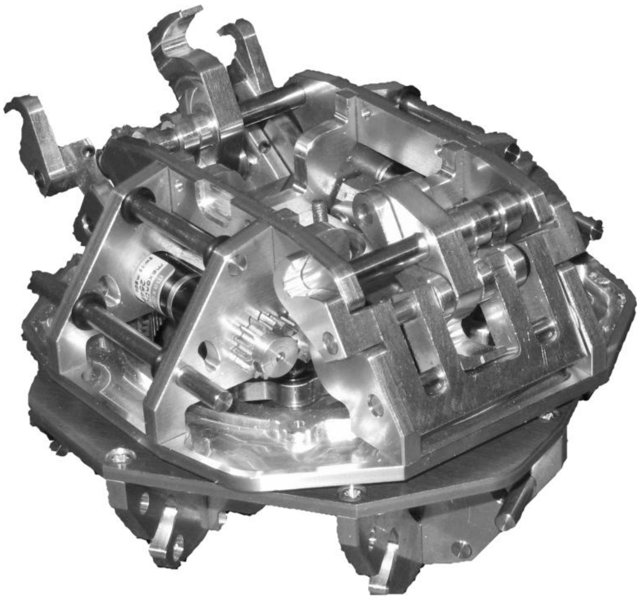

Fig. 3. The ATRON module, 11cm in diameter, without electronics and batteries.

Fig. 4. Carbon shoes (left) on the northern hemisphere are dragging along tracks on the slip-ring (right) allowing for transfer of power and data between the hemispheres.

the rotation trajectories why the cutoffs are necessary to allow a module to be rotated.

2) Connection Mechanism: Having settled on the double cone as the basic shape, connection between neighbors has to be *point-to-point* connections in contrast to e.g. the M-TRAN, CONRO, and I-cubes[8] who have *surface-to-surface* connections. A surface-to-surface connection method is an obvious advantage of the stress from connected modules hanging in the connection being distributed along the surface and the force exerted on the connector is minimized. To overcome with the problem of a point-to-point connection, a connector was designed that emulated a surface-to-surface connection by emerging three hooks from the surface of the active connector and grab into the passive connector as illustrated in figure 6. By connecting using three points, a surface-to-surface connection is emulated forming more reliable and stronger connection. 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 worm gear. While being power inefficient and relatively slow, this has the advantage of being power neutral while maintaining a connection. A connection takes 12.5 seconds to perform

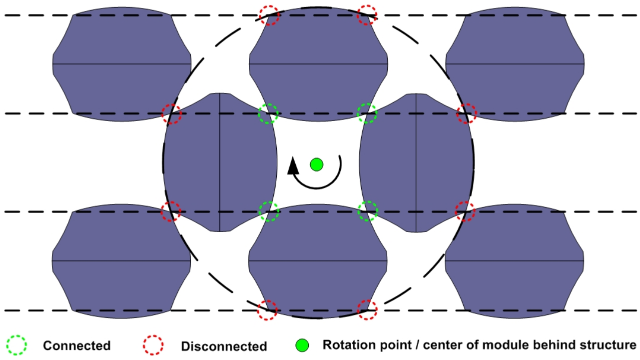

Fig. 5. Module trajectories calling for carvings in the two hemispheres.

and consumes a maximum of 18 joule when the motor is powered by 7.2 volt and is able to deliver a force of 200 N. While performing a connection takes 12.5 seconds and a disconnect takes 12.5 seconds as well, this is an issue we are improving by experimenting with different gearing and new motors. Preliminary experiments shows that we can lower the connect/disconnect time to 2.4 seconds in the current prototype. The connection mechanism was designed by Kristian Kassow.

C. Electronics Design

The electronics in the ATRON is heavily influenced by the fact that an ATRON module is split into two semi independent hemispheres

1) Power Supply: Aiming for a fully autonomous, self-contained homogeneous system, every module has to power itself. This is accomplished by equipping each module with two 3.6 V 980mAh ion-lithium-polymer cells[3]. This gives a total of 7.2 volt 980mAh for each module. However, simulations of organisms reconfiguring hundreds of modules show that modules residing in the middle of the organism tends to move little. Modules on the surface, on the other hand, expose large activity and may thus consume their energy before reconfiguration has completed. The solution to this is to give each module the ability to share energy it has in surplus with modules short of energy. To allow modules to share power, the ATRON module is designed so that when two modules are physically connected, they may transfer power if they wish to. The entire supporting metal structure forming the skeleton of an ATRON is electrically ground. This includes the hooks used for connecting. One of the hooks has an electrically insulated piece of flexible printed circuit board glued on top of it, so that when the module has connected to another module, it transfers positive voltage from one module to another — that way a common power line can be established throughout the entire organism.

Internally in an ATRON module, the power manager is build as sketched in figure 8. A power manager monitors the modules own power supply and the organism voltage and selects the best suited power source to power the

[3] Ion-lithium-polymer cells sponsored by Danionics A/S

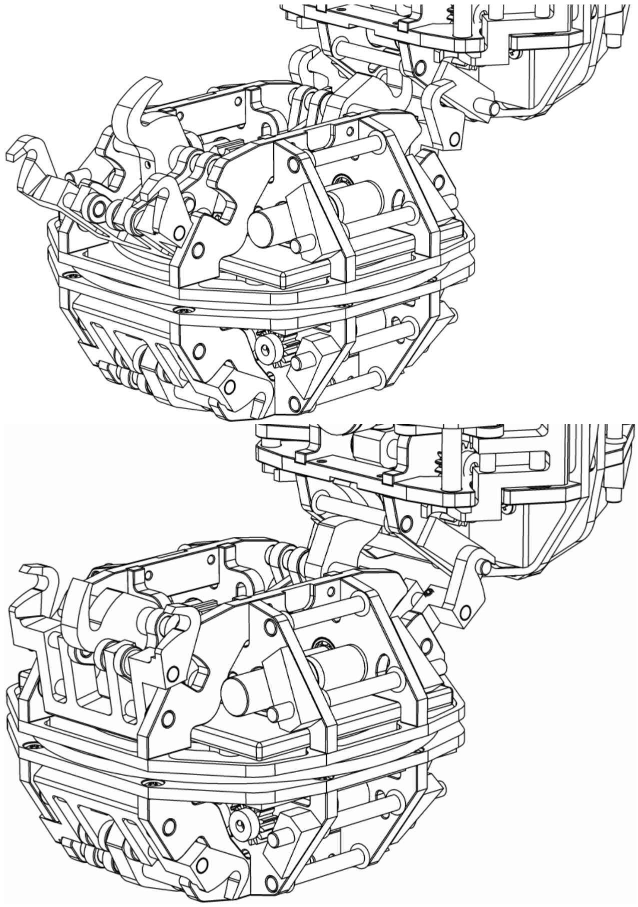

Fig. 6. CAD drawings of two ATRON modules connecting. **Top:** Connection has initiated. **Bottom:** Connection has completed.

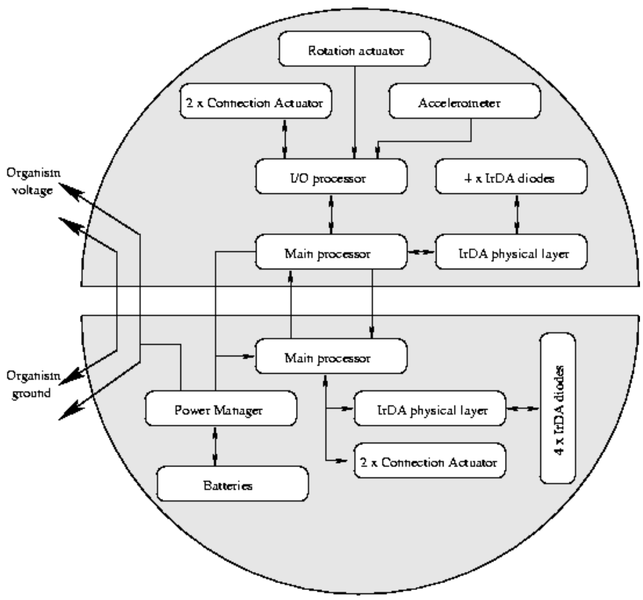

Fig. 7. Schematic overview of the electronics in an ATRON module. The northern hemisphere with accelerometer, rotation actuating and main processor is, via a five signals slip ring, connected to the southern processor which is managing power.

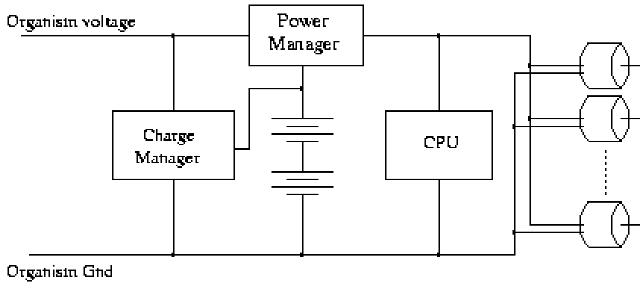

Fig. 8. Power managing system in the ATRON

module. In case the organism voltage is below a certain threshold with respect to the voltage across the modules batteries, the module may choose to share its power to the organism voltage.

The introduction of the organism voltage also provides a convenient way of re-charging an organism of ATRON modules. To re-charge an organism, it is only needed to connect a single module to an external power source. The modules forming the organism, can then by election decide who gets to re-charge its batteries first. The election may not be necessary in smaller organisms. The slip ring in the center of the ATRON is designed to carry 7A and a single ATRON module re-charging draws 500 mA when recharged at 7.2 V. It is therefore only necessary to limit the number of modules re-charging when an organism consists of more that 14 modules. Also, the organism voltage can serve as an external power supply when the modules are working in artificial environments such as a laboratory.

2) Processing Power: Since an ATRON module is a sphere split into to hemispheres that can rotate with respect to each other, it is obvious to consider an ATRON as two hemispheres instead of a single sphere. If processing power was put in one hemisphere only, several electrical signals would have to be transferred from the empty hemisphere to the one with processing power – at least 4 (for distance sensing) + 8 (for neighbor communication) + 4 (for connector actuation) + 2 (organism voltage) = 18 signals. Again, since the hemispheres can rotate with respect to each other, eventually they will rotate infinite thus leaving wired signal transfer out of the question. This issue calls for another solution, which was chosen and described in section IV-B; a slip ring. However transferring 18 signals on a single slip ring of the size available in an ATRON module would supersede the budget behind an ATRON module. Therefore it was decided to put an embedded computer in each hemisphere and thereby reducing the need for signals to be transferred to 5: Unregulated organism voltage, common ground, regulated voltage for the computer and data receive and transmit.

As illustrated in figure 7 the hemisphere without batteries (named *Northern hemisphere*) contains a main processor and an I/O processor. The main processor is a ATMega128 micro-controller from Atmel with 128Kb flash memory, 4Kb RAM and 4Kb EEPROM for permanent storage. The micro-controller runs a 16 MHz and is respon-

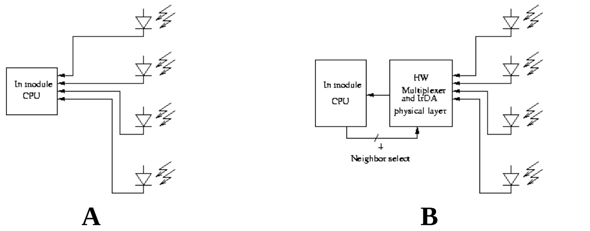

Fig. 9. Multiplexing of neighbor communication: **A:** Software multiplexing. Was too slow. **B:** Hardware multiplexing. Limited to one channel at a time, but substantially faster.

sible for communication with the northern hemispheres neighbors and the behavior of the entire module. In addition to the main processor, the northern hemisphere has a I/O processor. The I/O processor is a ATMega8 microcontroller from Atmel with 8 Kb flash, 1 Kb RAM and 512 bytes of EEPROM for permanent storage. The I/O processor runs a 1MHz and is responsible for reading the accelerometer, monitoring and actuation the entire modules rotation around equator and connecting and disconnecting with neighboring modules.

The hemisphere with batteries (named the *Southern hemisphere*) contains a main processor and a power manager. The main processor is identical to the one in the northern hemisphere; an ATMega128 from Atmel responsible for communication with, and connecting/disconnecting to/from its four neighbors. Also, the power manager has a processor monitoring the state of the batteries, controls whether to re-charge batteries or not, whether to share power or not and what power source to power the module from. This processor is a ATMega8 from Atmel identical to the I/O processor in the northern hemisphere.

3) Neighbor Communication: In order to have a self-reconfigurable organism of ATRON modules, every module must be able to communicate with its neighbors. To obtain this communication, every hemisphere has four sets of infra red diodes. Four diodes for transmission and four for receiving data, having each set placed close to the center of the module immediately below a connector pointing towards the center of the neighboring cell in the lattice. With the diodes placed in this pattern a module can exchange data with any module in the neighboring cell whether they are physically connected or not.

With the possibility of having four neighbors transmitting data at the same time, a hemisphere should be able to receive four fully independent signals at any given time. Initially, this was accomplished by connecting all four diodes for receiving to the processor and write four software UARTS as illustrated in figure 9A. Unfortunately tests showed that even with carefully optimized code, the bandwidth for a single neighbor could not exceed 1Kb/sec. As one of the goals with the neighbor communication is to allow behavior and low level software to spread throughout the organism, 1Kb/sec is unsatisfying, thus a trade off was made: The four received signals was being multiplexed in a hardware multiplexer, as in figure 9B resulting in one signal for the processor allowing for use of the built in UART of the processor.

To ensure reliable transfer of data between two neighbors, the physical layer of the communication conforms to the IrDA specifications and in the hardware abstraction layer the IrDA protocol stack is implemented for error checking and retransmission. Not only does this allow for a reliable transmission of data between neighbors, but it also allows a user to interact with an ATRON organism using a handheld computer, a laptop, cellular phone or any other device with an IrDA interface. Although the hardware multiplexing of the neighbor communication limits the communication to one neighbor at the time, it increases the bandwidth to 9,6 Kb/sec[4] and saves board space as the IrDA physical layer components needs not to be quadrupled.

4) Sensors: Every ATRON module is equipped with a number of both internal and external sensors. For external sensing any ATRON module has a 2-axis accelerometer for sensing tilt. However, since it is a two axis accelerometer only, a module can not tell if it is turned upside down or not. For further external sensing, an ATRON module can put its infra red communication in a special sensing mode, where the IrDA physical layer and the protocol stack is ignored and utilize its infra red diodes as primitive distance sensors. The purpose of this sensing, is to tell if a neighboring cell in the lattice is occupied or not. In addition with information on whether a possible module in the neighboring cell is connected or not, the distance sensing offers all information needed in order to recognize dead modules, external obstacles, or modules to connect with.

V. Discussion and Future Work

So far the ATRON module, its possibilities and capabilities has has been described. Even though the ATRON module seems very promising, there are some issues that deserves more attention. Some of these are:

- **Control complexity:** The presented design makes each ATRON module 8-times symmetric, in that the northern and southern hemisphere can be switched, or rotate either hemisphere $180°$ around the rotation axis, while maintaining the same global function of the module. Also, the final shape of the ATRON module allows one module to move to an adjacent hole in an otherwise fully packed structure, without colliding with other modules. The price paid for these two attractive attributes is that we do not have flat surfaces connecting, but rather point to point connections between modules, which makes the design of the connectors slightly more complex. Another issue is that modules cannot move themselves, only by actuation of the main joint in a nearby connected module. This causes high demands on the cooperation among the modules and we have previously published work on that issue, eg. [13], [14]
- **Mechanical stability:** So far ATRON modules have been mounted on test boards only, and reconfiguration with three modules has been tried. Under

[4]The limit is due to a limitation in the IrDA protocol stack being used.

these circumstances the mechanical properties did not show any unexpected behavior. However, we need to conduct experiments with substantially more modules to investigate the mechanical stability. Will a larger organism of ATRON modules oscillate when several modules are trying to align for connection? Will repeated operations wear the modules in ways we did not predict?

- **Electronics performance:** When having several modules connected, infra red communication may interfere and we still do not know how electrical noise will propagate through the organism. Those are issues we need to investigate in the time to come.
- **General improvements:** In certain areas of the development corners have been cut and development has been halter on these areas when a working solution was found. These areas need more attention, and optimization. One example on those areas are motor control and feedback. For the time being, motors are turned either on or off. Namely the center rotation could benefit from a motor control where starting and stopping slopes are used to reach the rotation speed. Another example is the distance sensing. As it is now, it is a very discretized sensing, and even though the information is valuable, a more detailed sensing would be preferred.

VI. Conclusion

In this paper we have presented the ATRON module. Although the ATRON module still needs the final adjustments, the overall design seems very promising. In addition to the tests we have already made where we have proved the modules capabilities to establish a physical connection, its capabilities to share power and move neighboring modules we still need to perform further testing of the modules capabilities and constraints. While we have great expectations to the ATRON module we also recognize that the algorithms needed to control a self-reconfigurable organism is complex (see [13], [14]) and that we will have to focus on that in the time to come together with other questions of which some are listed in the "Discussion".

A. Acknowledgements

This work is a part of the HYDRA project founded by the FET program under the European Union. Charlotte Ryberg, Danny Kyrping, Kristian Kassow, Lars Dalgaard, Leonid Paramonov, Richard Beck and other members of the AdapTronics Group has contributed to the work on the ATRON hardware.

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