ATRON Hardware Modules for Self-reconfigurable Robotics

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Abstract

We exploit a holistic behavioural and morphological adaptation in the design of new artefacts, and exemplify the potential of the new design principle through the construction of robotic systems that can change morphology. Here we present the ATRON design in which the modules are individually simple, attach through physical connections, and perform 3D motions by collective actions. We produced 100 ATRON modules, and performed both simulation and real world experiments. In this paper, we report on the ATRON hardware design and investigations related to the verification of the suitability of the ATRON module design for self-reconfigurable robotics.

Introduction

One of the main objectives of our work is to provide an architecture made up of simple building blocks, simple connections, and simple interactions, in order to allow end-users of our approach to design new artefacts in an easy manner. Indeed, the ATRON modules are simple building blocks that can be viewed as simple "cells" or "atoms" in a larger system composed of numerous of these individually simple building blocks. Ultimately, the design should allow a suitable way of performing self-reconfiguration by limiting the motion constraints in the system of building blocks as much as possible.

The connector mechanism of self-reconfigurable robots is known to be difficult to design because of the many constraints on the connector mechanism. Therefore, this problem was addressed with highest priority, since 3D motion in a terrestrial scenario demands attachment of modules to each other.

The methodology for choosing the right design for the connectors was to extract inspiration from the biological designs and to perform an extensive comparison of state-of-the-art, and afterwards make several design, realization and evaluation cycles for developing the final, mechanical solution for the modules. The biological designs pointed us towards a minimal design of "cells" that each should be very simple, but provide extensive possibilities for self-design and self-repair when combined in huge numbers. The survey of the state-of-the-art [1] told us that such a system based on these considerations would be novel. Related work includes the CONRO [2] and the M-TRAN [3] self-reconfigurable robotic systems. Other approaches include the Telecubes [5], the PolyBots [6] and the Crystalline [7]. Based on the inspiration from cell biology, we wanted to design a module to be simple and provide simple ways of avoiding many of the motion constraints known from other systems.

Figure 1. ATRON modules for self-reconfigurable robotics.

Module Design

The ATRON modules are placed in a surface-centred cubic lattice structure that corresponds to the titanium atoms in the $CuTi_3$ crystal lattice. The basic idea behind the ATRON modules is to have two half cells joint together by a rotation mechanism. On each half cell, there are two female and two actuated male connectors, by which a module can connect to the neighbouring modules. A major advantage for reaching the objective of producing many modules is that the ATRON modules are designed to be homogenous. Also, an ATRON module can switch or rotate either rotation axis 180°, maintaining the same global function of the module. Further, the shape allows one module to move to an adjacent hole in an otherwise fully packed structure (without colliding with other modules). So the module design seems to fulfill our objectives. Indeed, the design was guided by the considerations on how to reduce control complexity of self-reconfiguration by an appropriate module design. However, the design that meets these objectives demands strong and reliable point-to-point connectors, which also is achieved in the ATRON module with the novel, mechanical connectors, which are fast, strong and reliable.

A module may communicate with neighbouring modules through IR communication. When placed in the surface-centred cubic lattice structure, the modules can move in this structure to self-reconfigure into different overall arrangements or movements.

Figure 2. The first, second, and third (final) hardware prototype of the ATRON modules.

If a first ATRON module is attached to a second neighbouring module and detached on other connection points, the second neighbouring module may move the first ATRON module by turning around equator with the rotation mechanism. Hence, the first ATRON module may be moved to another position in the lattice structure where it may attach itself to another module in the structure and, for instance, detach itself from the second ATRON module that transported it to the new position.

As illustrated above, the reconfiguration of the overall system becomes a process of transitions in the lattice structure. Simulations (e.g. [xx, xx]) showed that, if we can perform the individual transitions in the hardware implementation in a reliable manner, numerous distributed control possibilities exist and will lead to self-reconfigurable and mobile systems. Hence, the module design and tests described below were guided by this demand.

Mechanical Design

The mechanical design was guided by the demand for strong point-to-point connectors in modules being able to lift another two modules and being placed in the surface-centred cubic lattice structure.

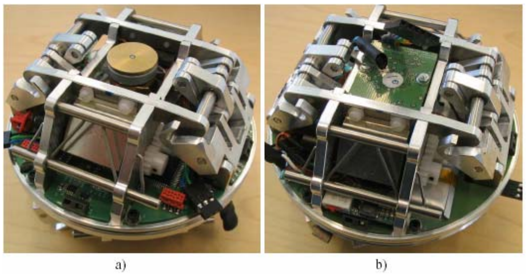

Figure 3. An ATRON module: a) Northern hemisphere, b) southern hemisphere.

Connectors

Based on the knowledge gained from the survey of state-of-the-art, three alternative connector designs were developed and considered. The first was based on a screw for holding two connected modules together. The second connector design was based on a pushing block, while the third is based on a triangular configuration of hooks, with a large base line for good rigidity. The screw mechanism was used in the first prototype, but shown not to be robust. Therefore, this design was abandoned. The remaining two approaches originated from the same idea and conformed to the same overall constraints. They differed in several mechanical aspects, the major differences between them being in the mechanical parts, which physically connect two neighbouring modules and in the rotation mechanism coupling the two hemispheres of the ATRON module. The two alternative connector designs were tested using two different hardware prototypes, and both connector prototypes performed comparably on most criteria, but the hook-based design was found to be most robust. The pushing-block design had a "weak" direction in which it sometimes would lock due to friction forces. For this reason the hook-based design was selected for the final design of the ATRON modules for the terrestrial scenario.

Active Connector

The push mechanism in the active male connectors is designed in such a way that a lead screw is used to transmit rotation to linear movement, and both lead screws and motors are installed in the same frame as the passive female connector parts. Figure 4 right illustrates the female frame parts where the motor and lead screw are installed. The push mechanism has been designed so that it is self-locking and very stiff, thereby ensuring that the connection between modules is always stable. The remaining parts of the active male connector mechanism are illustrated in figure 4 left.

The new teflon coated lead screw used in the actuation mechanism of the active male connectors has reduced the required torque from the connector motor, such that the connection time could be reduced to two seconds (the better efficiency compared to earlier prototypes made it possible to achieve the same force using a thread with greater pitch).

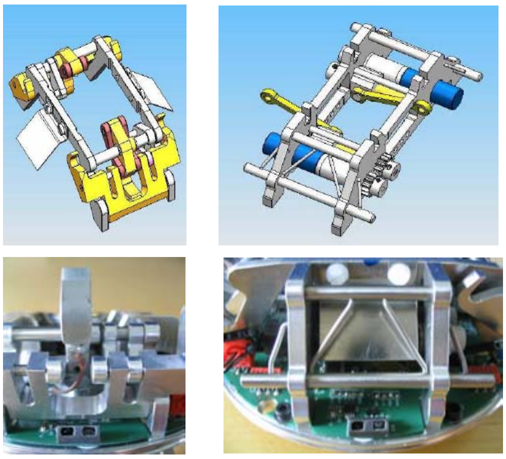

Figure 4. Left: Male hook that may transfer positive voltage. Right: An electrical isolated plate behind the female connector allows the male hook to touch the plate and power-share.

Centre Arrangement

A 1-stage planet gear in the centre of the module reduces the load requirements of the industrial gearbox with a factor of 118/10. Therefore the size of the gearbox is reduced compared to earlier prototypes, such that the centre motor and gearbox are fully contained in the northern hemisphere of the module.

Also, the identical frames used in the northern and southern hemispheres only differ in their centre part.

Slip Ring

To facilitate the ATRON module with intra-module power and signal distribution over equator, a slipring combined with carbon shoes has been installed in the module. The slipring is shown in figure 4b, where the inner five rings are used for electrical signals. The specialized slipring has been gold plated to ensure stable electrical connections. Furthermore the reflection abilities for the optical encoders are enhanced using a black diffuse background for better contrast (the outer fields are for the optical encoder). The encoders and carbon shoes are illustrated in figure 5a.

a) b)

Figure 5. Centre arrangement with gears and slip ring for transferring power and data between the two half spheres of the ATRON module. a) northern hemisphere, b) southern hemisphere.

Rotational Lock

The mechanism to drive the rotation of the module consists of the 1-stage planet gear, and the industrial planet gearbox and is thus not a self-locking transmission. The module has therefore been equipped with a solenoid that can drive a bar into rotational lock holes placed in both the northern and southern centre plates. The holes are positioned, such that the rotation can be locked in 90° intervals.

Wheel

The centre plates are made circular to aid manufacturing but also to add “wheel functionality” to the module. One of the centre plates is equipped with a O-ring (see figure 1). The O-ring acts as a tire, and a module can therefore be used as a wheel when placed in an upright position. This facilitates the creation of wheeling organisms.

Shell

The plastic shell illustrated in figure 1 has been designed to protect the electric and mechanical parts of the module and to ease the visual distinction and orientation of each module in a given structure. The shell has been produced in four different colors, which extends the visual distinction. Since the shell also gives a module a surface the infra-red proximity detection is made more stable and reliable. The shell also gives the ATRON module a more compact look.

Electronics Design

Every ATRON module has, besides its five main actuators, a solenoid actuator, a tilt sensor for measuring its two tilt angles with respect to the horizontal plane, eight Light Emitting Diodes (LEDs) useful for easy readout, a solenoid controlled plug for keeping the rotational angle between the two hemispheres at strict 90° intervals and an encoder disc placed perpendicular to the centre axis for measuring both the absolute rotational angle and relative rotational angle (for velocity calculations).

For neighbouring modules to inter-communicate, each connector is equipped with an infra red (IR) light transmitter and receiver allowing a wireless communication channel to be established between two modules. The IR diodes are also used for simple distance measurements.

Each ATRON module also contains two rechargeable Lithium-Ion Polymer batteries wired to enable power-sharing among connected ATRON modules. Power-sharing is necessary to power compensate the more motion active modules with power from the more motion passive modules. This is implemented through the connectors such that a mechanical connection between two ATRON modules also results in an electrical connection between the modules. A consequence of this is that re-charging the batteries of an ATRON module can be done even if it is placed within a structure formed by several ATRON modules.

To be able to electronically control all these hardware components several printed circuit boards (PCB) were constructed. On the Northern Hemisphere an ATmega8 (henceforth denoted *North-AT8*) microcontroller from ATMEL is responsible for reading the tilt sensor, controlling the centre motor in conjunction with the encoder disc, toggling the solenoid plug and opening and closing the two actuated male connectors.

The North-AT8 is also connected to an ATmega128 (henceforth denoted *North-AT128*) through the I^2C-bus. The North-AT128 is responsible for controlling the IR communication to and from the Northern Hemisphere but its main task is to function as the main coordinator of the components of the entire module (i.e. the main part of the *ATRONcontroller*).

On the Southern Hemisphere an ATmega8 (henceforth denoted *South-AT8*) is used for implementing the power control of the ATRON module. That is, charging the battery and making sure that a correct internal voltage levels is kept no matter the voltage level of connected modules or external power supply.

The South-AT8 is also connected to an ATmega128 (henceforth denoted *South-AT128*) through the I^2C-bus which is responsible for controlling the IR communication to and from the Southern Hemisphere and also for opening and closing the two actuated male connectors.

The two ATmega128 run at a clock frequency of 16 MHz and the two ATmega8 at 1 MHz.

The Northern and Southern Hemispheres are electrically connected through the rotational centre axis through a gold plated *slipring* (see above) with which carbon shoes maintain electrical contact also during rotation. The communication between the two hemispheres is conducted through a RS485 network of which the North-AT128 and the South-AT128 are the only nodes. The encoder disc for measuring the rotational angel is also placed on the slipring but is read optically. Figure 6 shows a block diagram of the electronic components in an ATRON module to which unit numbers in the following refer.

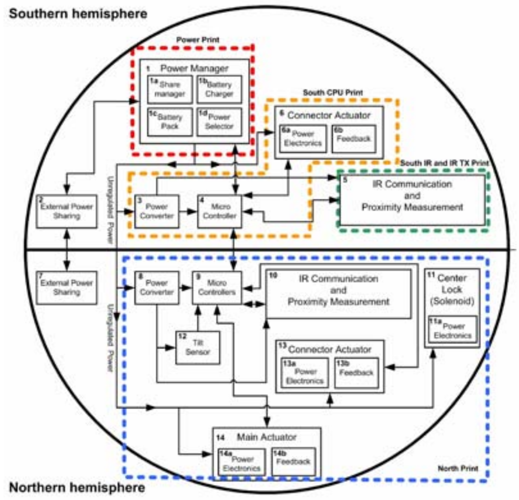

Figure 6. Overview of the electronic components in an ATRON module.

Tilt Sensor Interface

The Tilt Sensor Interface produces two DC voltage levels to the *North-128* proportional to the level of tilt (±90 degrees) in the planar x and y axis.

Connector Motor Interface

The connector actuator (figure 6, Unit 6 and Unit 13) is used for actuating the two male, active parts of a connection mechanism in each hemisphere. The actuator is a single DC motor rotating the arms until a firm connection is achieved.

Power electronics

The power electronics (Unit 6a and Unit 13a) used for controlling the DC motor is a fullbridge H-bridge build from an integrated circuit A3966.

Feedback

The only feedback from the actuators (Unit 6b and Unit 13b) that gives important information on the actuation is the power consumed by the motors. This is monitored through shunt resistors and when the current consumption reaches its highest level the arms are either fully extended or retracted and the motors are therefore stalled. This information is used to disable the motors to avoid overloading.

Centre Motor Interface

The Centre Motor Interface (Unit 14 called Main Actuator) consists of a brushless AC motor controlled by a dedicated driver circuit generating the necessary control signals (ASIC5660) and delivering the necessary power (L6234).

The torque delivered to the motor is controlled from the *North-AT8* which generates a PWM signal to the ASIC5660 with a duty-cycle proportional to the desired torque. Two output pins from the *North-AT8* controls the rotational direction and brake status (on/off), respectively.

Encoder Interface

The Encoder Interface implements the optical reader of the three outer rings of the slipring (see Figure 5b). The outermost ring has 108 "slots" which are read optically by two infrared readers (see Figure 5a) phase shifted 90° with respect to each other. This means that in one rotational direction one signal lags the other and if the rotational direction is changed it will instead lead the other. By feeding these signals to a D type Flip-Flop using one signal as clock and the other as data, the output will be either high or low depending on the rotational direction. This information along with the "clock" is read by the *North-AT8*.

The other two rings on the slipring implement a 2-bit gray-code (meaning only one bit changes at a time) allowing detection of 90° intervals when a transition occurs. This is used for accurate positioning of the rotational angle and is also read by the *North-AT8*.

Solenoid Interface

The Solenoid Interface (Unit 11) delivers power to the solenoid that drives the metal bar for the rotational lock mechanism. The solenoid is controlled by the *North-AT8*.

IR Interface

Unit 5 and Unit 10 are responsible for the IR communication and proximity measurement. Each hemisphere has four IR send-receive pairs (channels) able to communicate via the IrDA protocol at 9600 Baud or they can be used for proximity measurements. However, only one channel can be used at a time for either communication or for proximity measurement on each hemisphere.

The communication part is implemented using an IrDA physical-layer controller (MCP2120) that interfaces directly to the RS232 serial port of the *North-AT128* and *South-AT128* and the channel to use is selected by IO-pins.

The proximity measurement is implemented mostly in, but it relies on the ability of changing the strength of the light emitted thus a power control circuit was implemented by low-pass filtering a microcontroller generated PWM signal.

RS485 Interface

The RS485 Interface is implemented using two RS485 line-drivers connected through the slipring. One line-driver is connected to the RS232 serial interface of the *North-AT128* and the other similarly to the *South-AT128*.

LED Interface

The LED Interface consists of 8 LEDs which can be toggled on/off by the *North-AT128*.

Power Interface

The power management unit (Unit 1) is mainly responsible for supplying the ATRON module with power based on the current state of the batteries, the unregulated power and the current energy consumption. In addition, if the power manager detects that the voltage on the unregulated power supply meets a certain criterion it knows that the ATRON module is connected to a recharger and informs the battery charger that it may start charging the batteries. The power management unit is supported by four subparts each of which is described below:

Sharemanager

The Sharemanager (Unit 1a) pays attention to the modules battery supply and compares it to the voltage on the unregulated power supply and decides if it is safe to share power with other ATRON modules. The Sharemanager can choose how much current to deliver to the bus and, if necessary, entirely turn off the sharing.

Charger

The charging unit (Unit 1b) maintains all aspects of the actual charging of the battery pack and is ordered to start or stop charging by the power manager. Since the batteries are coupled and thus charged in series it is essential that the voltage difference between the two batteries is kept very low to avoid that the battery with the lowest potential drains the other.

This prevents proper charging and could potentially lead to battery malfunction. To account for this a voltage divider has been placed across one of the batteries and the voltage is measured by an AD-converter and compared to the series voltage also measured. This allows the power circuit to detect a skew voltage level and to react by preventing battery charging (however, we have also implemented a manual disconnect of the voltage divider when the module is inactive).

Battery pack

The batteries (Unit 1c) powering a single module consists of two series coupled Ion-Lithium Polymer batteries which can be charged to a maximum level of 4.2V each, giving a total of 8.4V maximum. Experiments on their operational time (before recharging is necessary) were conducted (see below) and the conclusion was that the batteries could sustain about 150 minutes at medium current load (300 mA).

Power Selector

The power selector (Unit 1d) monitors the voltage drop across the batteries and the voltage on the unregulated power supply. The highest is selected and used for supply. This ensures that a module will consume power from the source with the highest energy supply at any time.

Power converter

The unregulated power supplied from the Power Manager (Unit 1) in the Southern Hemisphere is passed through to the Northern Hemisphere. The Power Electronics (Unit 6a, Unit 11a, Unit 13a and Unit 14a) is directly connected to the unregulated power.

In each hemisphere the unregulated power is down converted to 5V by the power converter units (Unit 3 and Unit 8). The 5V from the power converters is needed to drive the basic electronic components and the micro controllers.

Module Tests

In order to test the mechanical and electronical design of the ATRON module, we performed a number of simple tests before going to the larger experiments related to self-reconfiguration and self-repair. These simple tests are reported below.

Battery Discharge Test

In order to test the operational time of an ATRON module with fully charged batteries, a burnout test of a module was performed. The code executed was a repetitious open-close sequence of the male connectors on the Northern Hemisphere. Current measurements during the test showed that the current used was somewhere between 200-400mA which is about half the maximum level. It was estimated that this level is a good representation of an average working condition.

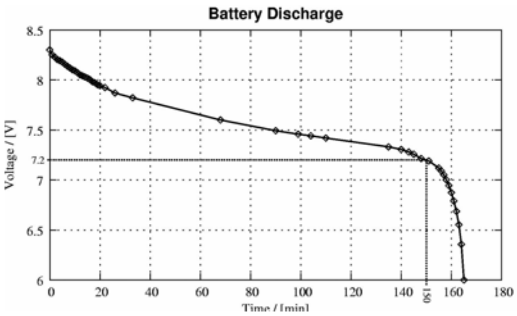

Figure 7. The battery discharge curve during burn-out test.

Figure 7 shows the voltage over the two series coupled batteries as the experiment progressed. It is noted that the starting level was 8.3V and after about 150 min. the voltage level had dropped to about 7.2V. From here it drops rapidly to about 6.0V in only 15 min. This discharge curve is consistent with the supplied data sheet for the batteries which also states that the battery voltage of any one battery must not fall below 3V where it may suffer damage.

From these information it can be concluded that 7.2V across the batteries is a good and safe choice for indicating that the batteries urgently need recharging. Furthermore the test showed that about 150 min. of operational time can be expected on fully charged batteries, which is acceptable.

Mechanical Deformation Test

A mechanical test has been performed, to measure the vertical deformation of a module structure due to slackness, elasticity and inaccuracies in the manufactured components and the angular tilt of the ball bearings. Figure 8 shows the setup used for the test where the red line illustrates a horizontal laser beam. The points **A** and **B** indicate where the deformation was measured.

A laser was placed on a table on the left side on the picture (not shown). The laser beam was levelled out horizontally by a mirror fixed to the steel bar seen on the right side of the picture and was adjusted such that the reflected beam was returned to the same horizontal level as its origin. After this the mirror was replaced by the module structure as shown in the picture such that the laser beam met the topmost point of the module attached to the steel bar (denoted **A** in the picture). A piece of card board was fixed at the topmost point on the leftmost module and the laser dot was marked at point **B** and the vertical displacement (the deformation) was measured to be 3.1mm. This value is surprisingly low but underlines the fact that the mechanical contruction is very stiff.

According to the manufacturer of the bearing the maximum angular tilt of the bearing is 0.0009 radians which result in a maximum vertical deformation due to the bearing of 0.42*mm*. Since our measurement shows a total deformation of 3.1mm, the remaining 2.68mm are therefore due to slackness, inaccuracies and elasticity in the components.

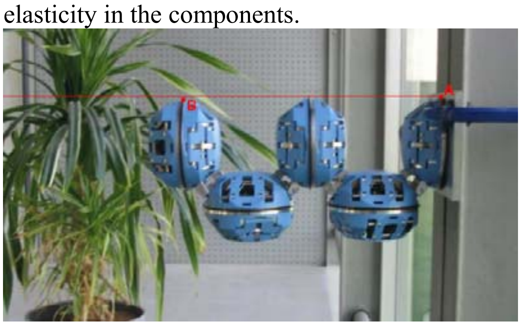

Figure 8. The setup for the mechanical deformation test.

Power Sharing Test

This test verifies that the modules are able to share power through their power sharing facilities. Figure 9 shows 4 pictures dumped form a video which illustrate a successful power sharing test.

Module **A** in figure 9 a) is a half passive module fixed to metal plate, and its power sharing circuit is externally connected to a power supply. Module **B** is switched off and is therefore supplied through its connection with module **A**. Module **C** is switched off.

In figure 9 a) Module **B** has started a connection to module **C**. In b) an electrical connection of the power sharing circuit has been established and the LEDs are turned on (marked with a circle). In c) the mechanical connection has completed and the two connectors in the upper hemisphere of module **C** is being actuated. In d) the connectors are fully extended.

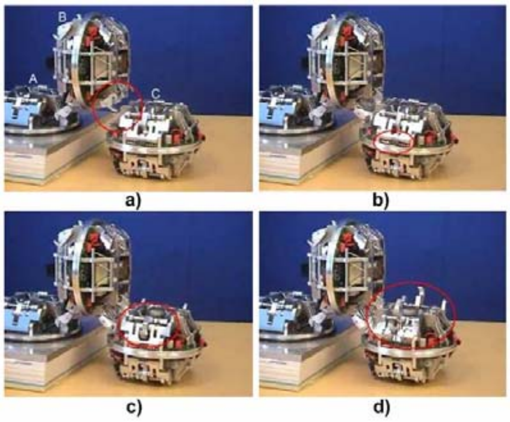

Figure 9. The setup for the power sharing test.

Rotation Test

In Figure 10 a setup for testing the rotational load abilities of an ATRON module is shown. The four pictures are screenshots from a video where the battery powered module **B** continuously rotates the two passive modules **C** and **D**. To obtain a stable platform, module **B** is connected to module **A** which is a half passive module fixed to metal plate.

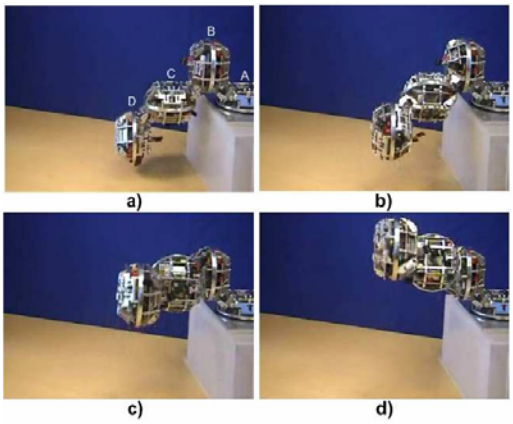

Figure 10. The setup for the rotation test.

In Figure 10 *a)* the initial position is shown. The rotation is initiated with an angular velocity of approximately 0.8 rad/s. In *b)* the modules have been rotated about 45° in counterclockwise direction and are approaching the 90° position *c)* where the inertial load is greatest.

Here the rotation is stopped and the solenoid lock is activated holding the modules in place for 3 sec. Hereafter the lock is released and the rotation continues as seen in *d)* pausing at the 180°, 270°, 360°, and 90° positions.

One of our initial design criteria for an ATRON module's rotational load abilities was that it should be able to smoothly rotate two other modules in a configuration as seen on Figure 10. This criterion was required to allow the overall system to have the necessary degrees-of-freedom to build complex structures and to limit motion constraints, and has now been verified to hold for the physical platform.

Misalignment Test

The purpose of this test is to show the ATRON module's abilities to connect to misaligned modules. Figure 11 shows 4 pictures of a successful connection between an active module and a passive misaligned module. In a) the active module has started the connection process. In b) the passive module is pulled towards the active module. In c) the passive module is twisted into its right lattice position.

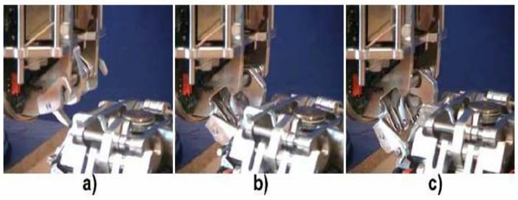

Figure 11. The setup for the misalignment test.

The misalignment corrections guides are illustrated in figure 12. The construction allows misalignment corrections of ± 5.7mm in the x direction, and at least ± 3.0mm in the y direction.

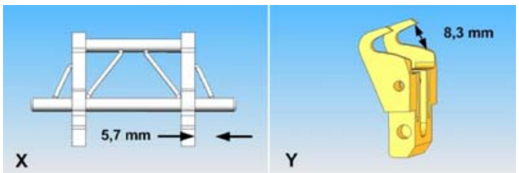

Figure 12. CAD drawings illustrating the possible misalignment corrections. (Left) The female frame part with guides, which allow misalignment corrections of ± 5.7mm in the x direction. (Right) The lower active male arm, which allows misalignment corrections of at least ± 3.0mm in the y direction.

Conclusion

We developed the ATRON design as simple building blocks with simple connections for simple interactions, in order to provide a design suitable for performing self-reconfiguration and for future miniaturization. Of great importance is the connector mechanism that is strong, fast and reliable despite being a point-to-point connector. Tests showed that the modules connect even when misaligned in the three dimensions, that a module can lift another two modules, that on-board batteries provide energy for approximately 150 minutes, and that power sharing between modules may be possible with the design outlined in this paper. We therefore believe the design to be suitable for self-reconfiguration and self-repair experiments (e.g. [8]), and will show such in future work with the 100 ATRON modules that we have produced now.

Acknowledgements

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