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Soldercubes: a self-soldering self-reconfiguring modular robot system

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Abstract Soldercubes are a self-reconfiguring modular robot (MR) system whose modules are light weight, low cost, and designed with manufacturability for large batch production in mind. The frequently cited promises of modular robotics—versatility, robustness, and low cost—assume the availability of large numbers of modules. However, modules in most MR prototypes are large, mechanically complex, expensive, and difficult to manufacture. Soldercubes partially overcome this contradiction through optimizing some components for volume manufacturing processes. With the integration of a soldering connector which weighs only 2 g and has no moving parts, Soldercubes are among the cheapest, lightest and smallest among comparable self-reconfiguring MR systems. This paper describes the Soldercube module design in detail, reports on experiments in a lattice configuration, explores non-lattice applications of the system, and discusses the effects of utilising volume manufacturing processes in module production. All Soldercubes design files are released as open source hardware.

Keywords Cellular and modular robots · Self-reconfiguration · Design for manufacturability

Supplementary videos for this paper are available at http://creativemachines.cornell.edu/soldercubes.

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1 Introduction

Modular robots (MR) are robotic systems composed of components that are homogeneous and near-homogenous in shape and function, and whose physical arrangement can be reconfigured. A subset of MR has the property of self-reconfigurability, meaning that the MR can autonomously change the topology in which its own modules are connected without external manipulation.

The following potential benefits have been repeated many times in literature (e.g. Goldstein et al. 2005; Ostergaard et al. 2006; Yim et al. 2000, 2007a, 2009; Stoy et al. 2010) as the promises of self-reconfiguring MR:

1. **Versatility:** For a system with n cube shaped modules, each cube face containing a rotation-invariant connector, there exist $(24)^n$ shape-distinct configurations. When considering actuated modules, the design space of kinematically distinct configuration grows exponentially with the number of modules. Thus, given a sufficiently large number of modules, a reconfigurable MR systems could be “programmed” to transform into different arbitrarily complex machines by re-arranging its own modules.
2. **Low Cost:** For modular systems where the number of modules per machine exceeds the number of module *types* by orders of magnitude, fabrication might benefit from economies of scale. With the availability of low cost mass produced modules, robot construction transitions from a complex integrated design task in a continuous design space into the discrete optimization of an assembly sequence of modules, increasing accessibility of the problem for humans and its suitability for automated design optimization.
3. **Robustness:** Modularity is a key concept in design for maintainability (Baldwin and Clark 2000). A self-

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reconfiguring MR system could repair itself by moving partially functional modules to locations in the robot where their missing functionality is not required. In MR that support the exchange of modules with the environment, modules can be discarded or replaced with new modules.

The current state of research in modular robotics does not yet support these promises. Kasper Stoy's remarks at the Robotics Science and Systems Conference 2005 about current MR being "(1) useless, (2) expensive and (3) they break all the time" (Stoy et al. 2010) still largely holds true today. Self-reconfigurability has been researched extensively in simulation, but hardware systems presented to date offer little utility beyond low level demonstrations of the concept with small numbers of modules.

The complexity of the individual modules is the primary obstacle to realizing the promises of MR. The higher the number of actuated degrees of freedom, sensor inputs, and connectors in each module, the higher the potential versatility of a MR assembled from these modules. However, this increased versatility comes at the cost of increased complexity and cost of modules.

Among self-reconfiguring MR systems there is no clear trend towards reduction in module complexity. Table 1 lists weight and volume per module of selected self-reconfiguring MR systems, spanning publication dates from 1993 to 2013, and neither property decreases considerably with more recent systems. Instead, the ongoing progress in miniaturization and integration of electromechanical components is employed towards producing more feature-rich but large and expensive modules; the models of the Symbrion project's CoSMO system by Liedke et al. (2013), for example, are controlled by a main controller clocked at 550 MHz and communicate on a 100 Mbit Ethernet network. Those MR systems that specifically address cost reduction achieve this through reduced feature sets, and no such system allows for self-reconfiguration of module assemblies (e.g. Wolfe et al. 2012; Revzen et al. 2010).

We attempt to find a middle ground between applying the progress in integration and miniaturization of components towards added module functionality, and trading functionality for reduced cost. From modeling the relationships between weight, used here as a proxy metric for the mechanical and manufacturing complexity, and both actuated degrees of freedom per module and active connectors per module using data in Table 1 we conclude that active connectors are the main driver of complexity in MR modules. Therefore, we chose to optimize the connection method of the modular robot towards reduced cost and increased manufacturability with the intention of having maximal effect on the same properties of the overall module. The resulting solder-

Table 1 Properties of selected three dimensional self-reconfiguring MR systems

Name	Ref.	d.o.f.[a]	Conn. Count[b]	Size (mm)	Weight (g)	No. built
Polypod	Yim (1993)	2 (2)	2 (2)	–	–	–
3D-Unit	Murata et al. (1998)	6 (6)	6 (6)	265 × 265 × 265	7000	2
CONRO	Castano et al. (2000)	2 (2)	3 (1)	108 × 25 × 25	115	–
Molecule	Kotay et al. (1998)	4 (4)	10 (10)	⌀ : 102	3200	1
I-Cube	Unsal et al. (1999)	3 (3)	2 (2)	85 × 37 × 18	205	–
MTRAN	Murata et al. (2000)	2 (2)	6 (3)	66 × 132 × 66	440	–
PolyBot	Yim et al. (2000)	1 (1)	2 (2)	50 × 50 × 50	200	56
Telecubes	Suh et al. (2002)	6 (6)	6 (6)	60 × 60 × 60	–	–
MTRAN-II	Kurokawa et al. (2003)	2 (2)	6 (3)	60 × 120 × 60	400	–
ATRON	Jorgensen et al. (2004)	1 (1)	8 (4)	⌀ : 110	850	100
Molecubes	Zykov et al. (2005)	1 (1)	2 (2)	100 × 100 × 100	625	7
Stochastic 3D	White et al. (2005)	0 (0)	6 (6)	100 × 100 × 100	–	4
MTRAN-III	Kurokawa et al. (2008)	2 (2)	6 (6)	65x65x130	420	50
ModRED	Nelson et al. (2010)	4 (4)	2 (2)	368 × 114 × 119	3170	
Roombots	Spröwitz et al. (2010)	3 (3)	10 (2)	220 × 110 × 110	1400	2
SMORES	Davey et al. (2012)	4 (4)	4 (3)	100 × 100 × 90	–	2
CoSMO	Liedke et al. (2013)	1 (1)	4 (4)	105 × 105 × 105	1250	2
M-Blocks	Romanishin et al. (2013)	N/A	6 (0)	50 × 50 × 50	143	8
Soldercubes		1 (1)	6 (6)	55 × 55 × 55	120	40

[a] Degrees of freedom and (in parenthesis) actuated degrees of freedom
[b] Connector count and (in parenthesis) number of actuated connectors
– = Information not found in literature

Fig. 1 Two Soldercubes assemblies consisting of a total of 27 Soldercube modules. Modules are located on an a tiled experiment substrate. The smaller assembly on the *left* is used to demonstrate locomotion in Sect. 4.4, pictured here while performing a step spanning two substrate tiles. The larger assembly on the *right* is a four-legged robot used to demonstrate synchronized motion between eight modules in Sect. 4.5

ing connector which we present in Neubert et al. (2014) is a connection method for arbitrary reconfiguring systems that is solid state, optimized for mass manufacturing, and weighs only 2 g.

The Soldercubes self-reconfiguring MR system, shown in Fig. 1 integrates the soldering connector into a modular robot system and is a first result of our work towards a system whose modules can be mass produced.

In addition to the material presented in this paper, Soldercubes are released as open source hardware. Complete design documentation of Soldercubes modules, including mechanical design files, printed circuit board (PCB) design files, and all embedded software source code, are available from the project page at http://creativemachines.cornell.edu/soldercubes.

2 Related work

2.1 Modular robots

The idea to construct modular machines whose local module-level interactions result in assembly-level behaviors such as self-replication and growth was first presented by von Neumann in 1948 (von Neumann and Burks 1966). At the time, the physical implementation was impeded by the technical complexity of constructing modules with computational, actuation, and connection capabilities. The concepts could, however, be demonstrated in simulation resulting in the definition of the term *cellular automata*. Four decades later, technological progress had moved the physical implementation into the realm of the possible. Beni (1988) formulates a mission statement for *cellular robotics*, followed by Fukuda and Nakagawa (1988) demonstrating CEBOT which is commonly cited as the first MR. The term *swarm* was coined by the same Beni as a synonymous "buzz word" for cellular robots (Beni 2004), but has since come to describe multi-agent behaviors (Sahin 2004), while MR are physically connected assemblies of modules (Yim et al. 2007a). MR might exhibit swarm behavior, and swarm robots might be modular, but neither classification necessitates the other.

A number of reviews on MR have been published, including the papers by Yim et al. (2002, 2007a, 2009) and Gilpin and Rus (2010), and the book by Stoy et al. (2010). Ostergaard et al. (2006), Moubarak and Ben-Tzvi (2012), and Spröwitz et al. (2013) also provide substantial reviews of aspects of modular robotics. Our own paper on the soldering connector (Neubert et al. 2014) reviews connection methods for self-reconfiguring MR. Table 1 lists a selection of three dimensional self-reconfiguring MR systems with properties that affect module complexity, namely actuator and connector counts, volume, and weight.

Table 2 Cost of MR modules

Name	Source	Cost (USD)
DoF-Box	Daidie et al. (2007)	120[a]
GZ-I	Zhang et al. (2008)	75[b]
M3Express	Wolfe et al. (2012)	190[a]
M-Blocks	Romanishin et al. (2013)	260[c]
Molecubes II	Zykov et al. (2007a)	349[d]
SMORES	Davey et al. (2012)	300[a]

[a] Batch size not specified
[b] 50 EUR
[c] Batch of 5 modules
[d] Batch size of 50 modules

2.2 Simple modular robots

Following CEBOT, the objective of research in modular robotics has been to meet the functional requirements of such systems and to demonstrate specific behaviors such as locomotion and self-reconfiguration on the small scale. The cost of implementation has rarely been considered and only for few systems has the cost per module been quoted; those systems are listed in Table 2.[1]

In recent years, low cost and low complexity has been a stated design requirement for some MR systems: M3express (Wolfe et al. 2012), ckBot (Revzen et al. 2010), GZ-I (Zhang

[1] Even where the cost of fabrication and assembly is available, reported prices normally exclude the cost of assembly labor, such as PCB assembly, and the cost of fabrication for in-house fabricated components. In addition, the batch size for which prices are quoted is omitted. This makes a direct comparison of MR in the cost dimension difficult.

et al. 2008), DoF-Box (Daidie et al. 2007), and Molecubes II (Zykov et al. 2007a) have been presented as affordable MR systems for applications in education. Of those, the Molecubes II module's feature set comes closest to that of Soldercubes with one actuated d.o.f. However, Molecubes II lack active connectors and are therefore only manually reconfigurable while both cost and module volume are marginally higher than for the Soldercube module. By further reducing the functionality of the module, such as requiring manual assembly with screws or pins, no built-in electrical connection between modules, fewer connector surfaces, or limited range of the rotational degree of freedom, ckBot, GZ-I, DoF-Box and M3express achieve even lower cost per module.

The M-Blocks system by Romanishin et al. (2013) attempts to reduce complexity of both actuation and connection by using angular momentum for both movement of the module and overcoming the connection force exerted by permanent magnets. M-Block modules have zero actuated degrees of freedom and flip over their edge by applying a brake to a fly wheel. This approach results in a part cost of only USD 260, a weight of 143 g with dimensions of 50 mm cubed per module.

Kilobot by Rubenstein et al. (2012) is an example for a low cost mobile modular robot that can be used to demonstrate two-dimensional swarm behaviors. Kilobot modules cost only USD 14 and communicate with each other through RGB light signals, but cannot physically connect.

The idea to achieve a lower per-module cost through mass production of MR modules has been mentioned frequently before, for example in the context of "Programmable Matter" by Goldstein et al. (2005). However, design for manufacturability principles have not been applied to any self-reconfiguring MR. The record for the largest number of modules produced for a self-reconfiguring MR is held by the ATRON system with 100 modules produced (Yim et al. 2007a). Among manually reconfigurable MR systems one example of mass-production exists: 50026 modules of the Cubelets™ system by Modular Robotics Inc, a lattice type non-homogenous MR marketed as an educational toy, have been produced as of October 2013 (Schweikardt 2013, Personal Communication).

2.3 Thermal connectors for modular robots

Several thermal connection methods have previously been proposed for MR connectors: Miyashita et al. (2008) developed a water-based connection method where to form and hold a connection water is frozen between adjacent modules. Peltier elements are used for cooling. This method has the disadvantage of continuously requiring power to retain the connection. Wang and Iida (2013) employ a hot melt adhesive as binder material. This method requires power only during the connection and disconnection processes. Diller et al. (2013) used the same binder material as the Soldercubes system, Field's Alloy, for forming bonds between assembly modules. However, these passive modules rely on external heating by lasers for melting the binder.

3 Module design

The modules of the Soldercubes MR system are designed to be basic building blocks of modular machines that can reconfigure internally as well as exchange modules with their environment. Design requirements for the individual Soldercubes modules can be derived from the required features of the assembled modular machines. Module assemblies must be able to perform the following scenarios without external manipulation:

1. Growth of robots through acquisition of modules from the environment into a robot.
2. Rejection of modules from the robot into the environment.
3. Change of relative module arrangement inside the robot.

The following sections discuss the components of the Soldercube module: connection method, actuation, sensors, energy storage, and electronic design.

3.1 High level design considerations

3.1.1 Dimensionality

While two-dimensional MR systems such as Catoms (Kirby et al. 2007), XBot (White and Yim 2009), and Chobie-II (Koseki et al. 2007) have the benefit of design simplicity, they do not easily map to real-world applications. In order to implement meaningful demonstrations of growth and robot interaction, Soldercubes are a three-dimensional system.

3.1.2 Topology type

MR are traditionally classified into chain, lattice and mobile type (Stoy et al. 2010). To avoid the difficulty of arbitrarily aligning modules in 3D space, Soldercube modules are constrained to only connect to and disconnect from other modules when aligned with a 3D grid in all demonstrations presented in this paper. This inherently makes Soldercubes a *lattice type* modular robotic system. However, Soldercubes are mechanically and electrically suitable for use in chain topology module assemblies, but the control and sensor integration necessary for chain behaviors has not yet been implemented. Section 5.3 of this paper discusses hardware extensions towards mobile robots assembled from Soldercubes.

Table 3 Soldercube Module Types

	Actuation Module	Structural Module	Energy Module
Actuator	✓	✗	✗
Battery	✗	✗	✓
Connectors	6	6	6
Adjacency Sensors	4	6	6
Addressable Controller	✓	✓	✓
Accelerometer	✓	✓	✓
Weight (g)	120	76	138
Cost (USD)[a]	315[b]	94	108

[a] Includes cost of parts and fabrication but not assembly
[b] Without slipring, that is without support for infinite rotation, has an estimated cost of USD 193. Cost estimates are based on price information as of April 2014 and assume components are purchased for producing 50 modules of each module type

3.1.3 Heterogeneity

Soldercubes were originally designed to be a homogenous MR system where robots consist exclusively of actuated modules. Subsequently, *structural modules* that have the same shape and connector as actuation modules but lack the actuator were introduced to reduce manual assembly labor required to prepare experiments with tens of modules. The *energy module* is the third module type, containing a rechargeable power supply. A comparison of these three basic module types is given in Table 3. The shape of all three module types, however, is identical. Finally, the extensibility of Soldercubes into a general purpose MR assembly system has been demonstrated by introducing further special purpose module types. Section 5 describes a selection of such specialized module types.

3.2 Connection method

A high number of connectors per module greatly increases the number of possible module arrangements and therefore the versatility of a MR system. At the same time, it contributes to cost and complexity of the module. These properties make the connector a prime target for optimization when the goal is to develop a low complexity easy to manufacture robot module.

In Neubert et al. (2014) we introduced a self-soldering connector that weighs only 2 g and has an overall thickness of only 3 mm. It contains no moving parts and can be mass-manufactured using widely available PCB fabrication and assembly processes. Soldercubes integrate this connector into a self-reconfiguring MR system. Despite its simplicity, the soldering connector has sufficient mechanical strength to support tens of Soldercubes modules in tension and includes electrical connection for signal and power transfer between modules.

The soldering connector consists of a two layer PCB whose outward facing side contains soldermask-free copper pads covering 75 % of its surface. These copper pads are covered with a meniscus of the low melting point alloy of composition 51 % In, 32.5 % Bi, 16.5 % Sn, commonly referred to under the name “Field’s Metal”. The inward facing side of the PCB contains resistors used as heaters, as well as a MOSFET acting as a switch for the resistor array, and a connector. Figure 2 shows top, bottom, and side views of the soldering connector.

Each Soldercube module exposes six self-soldering connectors on its surface, one per side of the cubic base shape of the module. This allows for a maximum of six concurrently connected neighbors per module.

To form a connection, two modules are brought into immediate adjacency, normally through appropriate actuation of the modular assembly they are part of. One or both modules then activate the resistive heaters resulting in heat transfer into the low melting point alloy. Once the low melting point alloy is heated above its melting temperature of 62°C the adjacent liquid metal menisci merge and, after cooling, are mechanically and electrically connected. Surface tension of the low melting point alloy allows for this process to occur in any orientation.

Soldering connectors are versatile and can be implemented in almost arbitrary size by the selection of appropriate components. Volume and surface area of the Soldercube module are driven by the space requirements of the module’s internal components. The shape of the soldering connector implemented in Soldercubes, an approximately annulus shaped flat area sized 650 mm^2 (1 in^2), fills the remaining portion of the flat sections of surface area after accounting for all other functions. The connectors are embedded into the module shell such that the outer surface of the connector PCB is 0.6 mm recessed from the module shell surface, resulting in a 1.2 mm gap for the Field’s Metal binder material between connected connectors. Miniature screws and adhesives are used for fastening the connectors into the module shell.

Each connector is powered and controlled through a flat flexible cable (FFC) that is inserted into low insertion force connectors on the main controller board inside the module. The resistor array acting as heater on the connector consists of eight 10 Ω resistors rated at 1.0 W each. The resulting power consumption during connection or disconnection is approximately 7 W. A heating duration of 10 s is sufficient to melt the binder material in air at room temperature. Because there is no active cooling, the rate of cooling during the solidification of the connection is smaller than the rate of heating. In the experiments described in Sect. 4 we erred on the side of caution, allowing the connector to cool for up to 60 s. Feedback control of the heating process with an on-board temperature

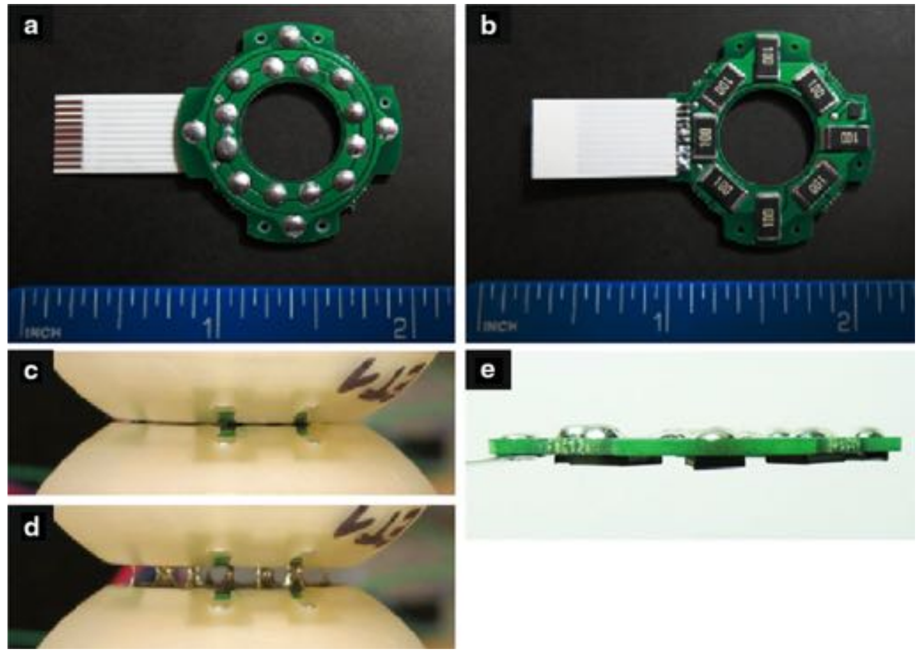

Fig. 2 Self-soldering connector: **a** *Top view* showing 16 connector pads covered with a low melting point alloy on a circular PCB that is part of the outer surface of the Soldercube module. **b** *Bottom view* showing eight resistors heating up the low melting point alloy during the connection and disconnection process. **c** *Side view* of two soldering connectors embedded in module shells while connected and **d** showing the low melting point alloy in liquid state with the connectors spaced by 2 mm. **e** *Side view* of the soldering connector PCB with overall thickness of 3 mm

sensor would be a valuable direction for further work to minimize the time to form a connection.

Allowing for low cost mass production was the primary motivation for developing the soldering connector. Component cost of each connector is USD 2.95, including custom PCB fabrication and custom FFC fabrication for 800 connectors at USD 0.24 and USD 2.01 each, respectively. Assembly of the PCB was quoted at USD 4.80 each at the same batch size. Finally, applying Field's Metal involves two dipping and one wash step. This process was performed manually but can be readily automated into a batch process with a process duration of less than 30 s per connector.

Mechanical strength and durability are two important considerations in connector design. To quantify the former for the soldering connector, tensile tests were performed with soldering connectors fastened into mock modules. Over a series of 20 tests, the average load at failure was measured as 173 N with a standard deviation of 46.4 N. While lower in absolute terms than published strengths for mechanical MR connectors, this compares favorably when put in relation to weight. The soldering connector could carry 8800 connectors, or 80 Soldercube modules.

A durability test was also performed during which soldering connectors connected to a robot arm underwent repeated connection-disconnection cycles under controlled conditions. During each connection cycle, the mechanical and electrical soundness of the connection were tested. The average number of cycles before failure was measured at 220.

As a thermal joining process involving a phase change, the connection process performed by the soldering connector may be considered either welding or soldering: If one choses to consider the low melting point alloy as integral part of the Soldercube module, this connection process is equivalent to welding. We prefer to see the alloy as a binder material meaning that the connection process is soldering. This view is supported by the fact that over a connection-disconnection cycle some binder material may move from one module to another, the root cause of failures during the aforementioned durability tests.

A more detailed description of the design and validation processes for the soldering connector as well as a review of other connection methods for MR are given in Neubert et al. (2014).

3.3 Actuation

The number and placement of degrees of freedom (d.o.f.) within the module define the design space of mechanisms possible with assemblies of modules: For chain type assemblies the placement of d.o.f. can restrict the work envelope of a kinematic chain of modules or partition space; for lattice type module assemblies the same choices limit the paths on which modules can travel within the assembly.

Most recent lattice type self-reconfiguring MR contain one or 1.5 rotary actuators per lattice cell while earlier systems attempted to house up to six actuated d.o.f. per lattice cell (e.g. Murata et al. 1998) and some explored linear actuation (e.g. Suh et al. 2002). The trend towards smaller d.o.f. count per lattice cell is likely due to the insight that large numbers of simple modules are more likely to meet the goals of versatility, low cost, and reliability than fewer complex modules. The design of the Soldercube module follows the same approach and minimizes size, cost, and part count of each module by including one actuated d.o.f. only.

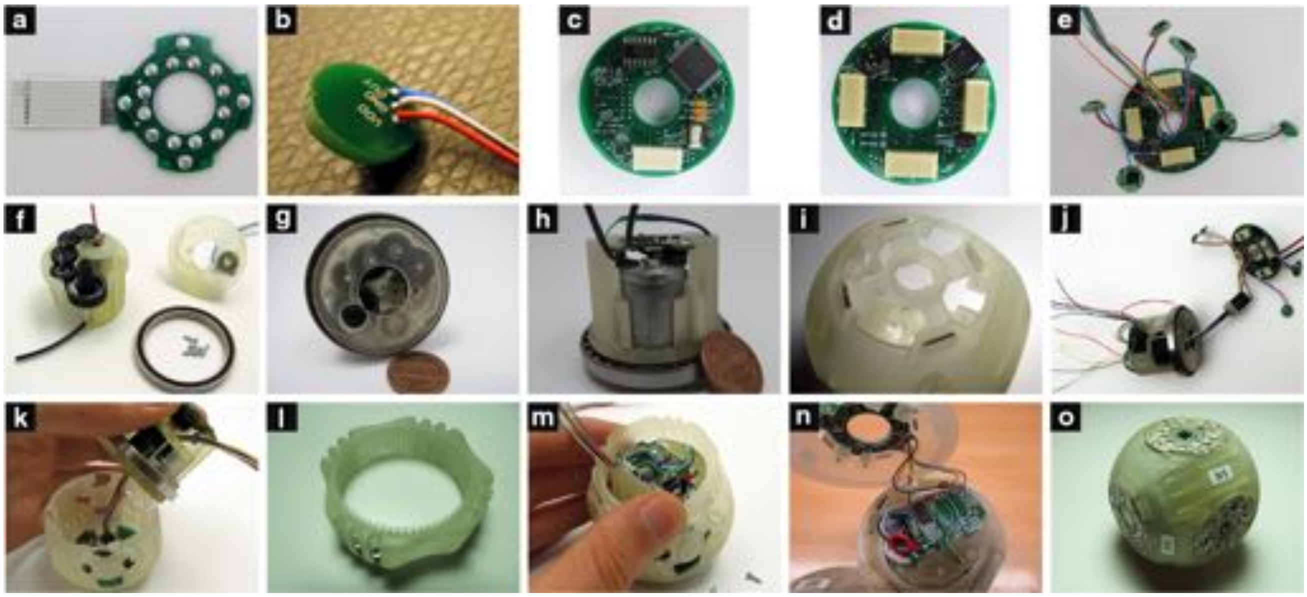

Fig. 3 Components of the Soldercube actuation module. **a** Soldering connector with attached flat flexible cable connector. **b** Adjacency sensor PCB. **c** Main controller PCB, *top view* and **d** *bottom view*. **e** Main controller PCB with adjacency sensors and slip ring wires attached. **f** Gearbox components including Dynamixel DC motor, gears, and potentiometer, and bearing. **g** Top view of assembled gear box showing center channel for wires connecting the two modules halves rotating relative to each other. **h** *Side view* of gear box. **i** Module shell showing one flat surface with cavities for one soldering connector and adjacency sensor PCB. **j** Assembly of main controller PCB, adjacency sensors, slip ring, and gear box. **k** Assembly of gearbox into module shell. **l** Internal gear. **m** Assembly of internal gear into module shell. **n** Final assembly step of connecting the smaller part of the module shell consisting of a single rotating face to the gearbox. **o** An assembled Soldercube module

MR system with rotational d.o.f. can be broadly divided in those whose modules cover one cubic grid cell and have one actuated d.o.f., and those whose modules contain three actuated d.o.f. in two grid cells. Within the first category, several options for the orientation of the single actuated d.o.f. within the module have been explored in previous work: In the Molecubes system by Zykov et al. (2007b), the actuator is aligned with the long axis of the cubic lattice cell rotating equal halves of the module relative to each other. The Cubelets system's "Rotate Cubelet" rotates one face of the cube shaped module relative to the other five faces. CoSMO (Liedke et al. 2013) sacrifices two out of six possible connector faces to allow two L-shaped halves to change their relative positions through rotations. Examples of the latter category where one module spans two cubic lattice cells are the Roombot (Spröwitz et al. 2010) and Superbot (Salemi et al. 2006) systems. The introduction of the third d.o.f. removes the bipartition inherent to 1-d.o.f. systems,[2] while the single-lattice-cell designs increase reconfigurability.

Based again on the maxim to minimize the module's size, cost, and maximize manufacturability and reconfigurability, Soldercubes are designed as single lattice cell modules. In an iterative design process, a lattice-aligned axis of rotation resulted in the minimal overall module dimensions and was therefore chosen for the Soldercubes system. Figure 3 shows components and assembly process for the actuated Soldercube module, and an exploded view is shown in Fig. 4.

For the single actuated d.o.f. per Soldercubes module, components of a Dynamixel AX-12A servo motor by Robotis Inc were rearranged to make optimal use of the module's interior space. This product supports infinite rotation and the specified stall torque of 5.39 N m would be sufficient to support approximately nine Soldercube modules in a cantilevered configuration. The integrated potentiometer has a resolution of 0.30° but has a dead band of 60° on wraparound during which no readings are available. Because in applications in the lattice configuration Soldercubes only interact when aligned with a 3D grid, only rotations in 90° increments are required allowing to accommodate for the dead band of 60°.

While the servo motor package of the Dynamixel AX-12A product is convenient for many applications, its packaging is not ideal for fitting into a cubic space. Therefore, the AX-12A components are rearranged and placed in a custom 3D-printed enclosure. First, the four gears of the AX-12 gearbox as well as the DC motor are rearranged to open up a free channel through the center of the gearbox for wire routing. Second, the Dynamixel's output gear stage engages with a 3D-printed internal gear mounted inside the module's shell

[2] In systems with one rotary d.o.f. per module, space is divided into two halves: Lattice cells can be thought of as arranged in a three dimensional checkerboard pattern. Modules in "black" lattice cells are not able to move to "white" cells and vice versa (Spröwitz et al. 2010; Salemi et al. 2006).

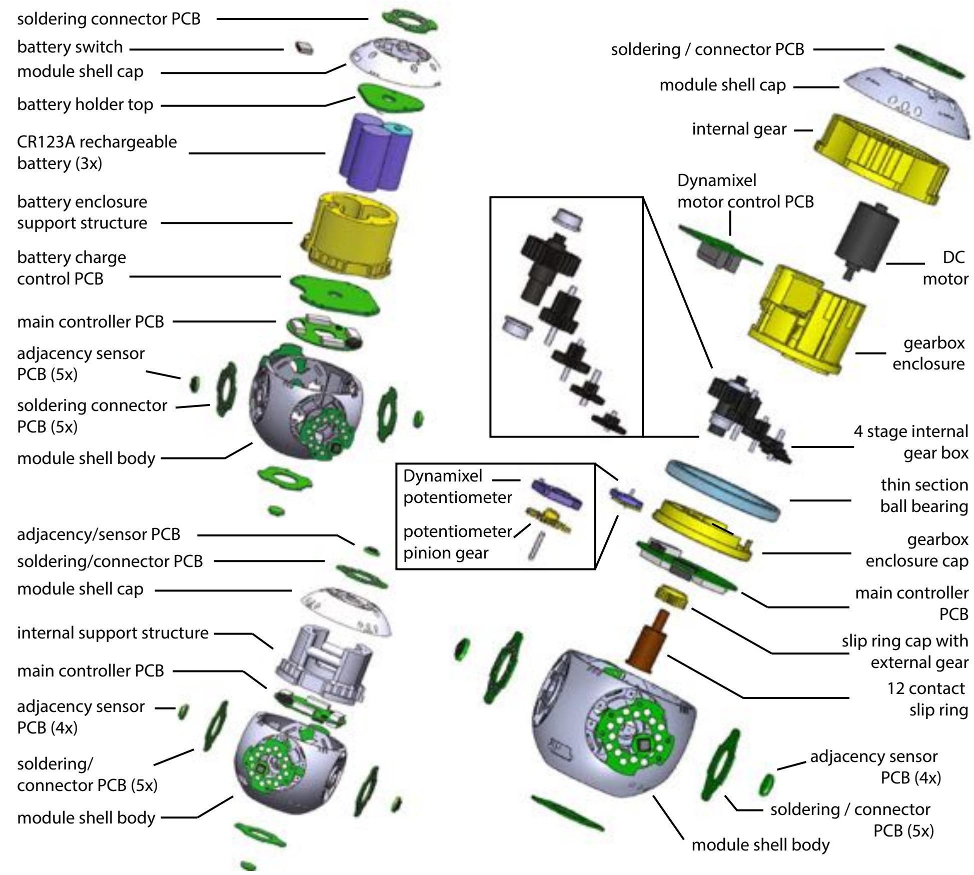

Fig. 4 Exploded views of energy (*top left*), structural (*bottom left*), and actuator (*right*) Soldercube modules, CAD drawings. *Light grey* 3D-printed cube shell, *green* PCB, *yellow* internal 3D-printed components, all *other colors* see annotations (Color figure online)

body increasing the gear ratio by a factor of 2.36. Third, the voltage regulator of the AX-12A controller board is unsoldered and mounted mirrored from the opposite side of the PCB to reduce the overall thickness of the PCB. Finally, the potentiometer is removed from the AX-12A controller PCB, combined with a custom 3D-printed spur gear and mounted to engage with the gear placed on the slip ring. Figure 3f–h shows stages of the gearbox assembly process.

In robot modules with one actuated rotational degree of freedom, the problem of cable strands twisting needs to be overcome. Soldercubes modules contain one 12-contact Moog SRA-73540-12 slip ring with each contact rated at 2 A. Eight wires are reserved for power transmission, allowing for up to 8 A to be transferred through the rotating joint inside the actuation module. Of the remaining four wires in the slip ring, one is used for the communication signal bus, one for controlling the connector on the rotating module part away from the main control PCB, one for sending commands to the servo controller PCB, and one for the adjacency sensor signal. The space requirements of the already small slip ring package are further reduced by replacing the outer shell of the plastic housing with a small 3D-printed spur gear shaped cap. The slip ring component alone accounts for approximately half of the total component and fabrication cost of the Soldercube actuation module. For some applications it might therefore be a suitable tradeoff to sacrifice infinite rotation capability for reduced cost.

The actuation module is split into two sub-assemblies which are actuated to rotate relative to each other. One side consists of a shell with five of the cube's outward facing connectors. Mounted inside this shell are the module's main controller PCB, as well as the internal gear around the circumference of the interior space of the shell. The other subassembly has only one soldering connector and is attached to the motor and gearbox assembly which fill most of the space inside the module. The load bearing interface between the two parts of the actuation module is provided by a four point contact thin section bearing with 1.5 in bore. The gearbox is designed to fit inside this bearing and clamps it between its two parts as can be seen in Fig. 3g, h. The outer flange is similarly clamped between the cube shell and the large internal gear.

The module shell is in the shape of a cube with rounded corners. Each of the flat sides has a surface area of 821 mm^2, or 27.1 % of the lattice cell's side and is shared between the soldering connector PCB, an adjacency sensor and alignment magnets. The outer dimensions of the actuation module are such that it fits a 55 mm cubic grid cell of whose volume it fills 75 %, and the total weight is 120 g. Among comparable 3D self-reconfiguring MR designs the Soldercubes

Table 4 Soldercube Module Specification

Actuation	
Actuator	DC motor
Gear ratio	1/599
Max. rotational speed	$150^\circ\ s^{-1}$
Max. torque	5.39 N m
Sensing	
Potentiometer [a]	300° coverage
Accelerometer	ST LSM303DLHC
Adjacency sensor (×6)	Osram SFH 7741-Z
Communication	
Inter-module	1-wire serial bus, 9 kBd
Servo control	1-wire serial bus, 1 MBd
Communication	
Supply voltage range	9 to 14 V
Rechargeable battery (×3)	Tenergy RCR123A
Power consumption	
Idle	100 mA @ 11 V
Heating	600 mA @ 11 V

[a] Component of Dynamixel AX-12+ servo motor package

module is the lightest and smallest. The efficient placement of components and integration of several functions into single components requires very finely detailed structural components Table 4. These components are 3D-printed in Objet Fullcure 720 material using an Objet Connex 500 polyjet resin printer set to a 16 μm layer resolution.

3.4 Sensors

The sensors included in the Soldercube module are limited to those necessary for a modular robot to determine its configuration and orientation in space.

Each of the six connector surfaces of the module contains one binary output adjacency sensor to determine if a neighboring module is present.[3] The adjacency sensor PCB contains only the Osram SFH 7741-Z active infrared proximity sensor together with its essential peripherals. The range setting resistor is chosen for detection at 5 mm range to detect only directly adjacent modules but never modules one lattice cell away. If the proximity sensor were to operate continuously, two facing sensors could interfere resulting in false readings. This risk is minimized by only providing power to the sensor momentarily when a reading is requested. While design for manufacturability would suggest integrating the adjacency sensor with the soldering connector PCB, this is not possible because no part of the module may extend beyond the boundary of the lattice cell. Therefore, the adjacency sensor is implemented as a separate 8.5 mm diameter PCB. The cavity in the center of each flat module face is designed such that the PCB snaps into place during assembly.

The main controller PCB of each module contains an integrated magnetometer-accelerometer package, LSM303DLHC by ST Microelectronics, which provides information about the orientation of the module in space. In the experiments described in this paper the magnetometer component of the device remains unused. In addition to operating as a sensor, the accelerometer is used as a noise source to seed the random number generator to provide non-deterministic wait times in the communication protocol.

Finally, the Dynamixel AX-12A controller's control table includes a torque reading which can in theory be used to determine the applied torque, but practically is neither precise nor repeatable enough to provide useful information. If functional, this feature would allow for force feedback control of the modular assembly's interactions with the environment.

[3] The actuation module is an exception and only contains four sensors. The remaining two, located on the rotation axis, are omitted due to space constraints.

3.5 Electronic components and module control

Each Soldercube module is individually programmable and has exclusive control over its connector, actuator, and sensors. Only three distinct electrical lines are exposed externally through the soldering connector: two for power supply and one signal line. Both the signal and power lines of all six connectors per module are directly connected in every module, forming assembly wide power and signal buses.

Each Soldercube actuation module contains a total of 14 printed circuit boards. Twelve are mounted facing outward in the module shell: six soldering connector PCBs and six adjacency sensor PCBs. Inside the module the modified PCB extracted from the Dynamixel servo motor acts as motor controller. Finally, a custom designed main controller PCB is also mounted in the interior space of the module and acts as a hub, connecting to all other PCBs in a star topology.

All but three of these circuit boards are on the same side of the rotational joint as the main controller PCB in the actuation module. One connector PCB, one adjacency sensor, and the motor controller PCB are part of the smaller section of the module shell on the other side of the joint, and the slip ring connector described above is required to connect them electrically to the other components of the module.

The main controller PCB is shown in Fig. 3c, d. Its central component is the 8bit Atmega1284(P) microcontroller, which is programmed to control all functions of the module including switching connectors, reading all sensors, sending motion commands to the servo motor controller, and communicating on the communication bus. Soldercubes can be reprogrammed without mechanical disassembly by inserting the custom ISP programming cable through an opening in the module shell. A small number of additional functional components are present on the main controller PCB: A separate resonator allows for the processor to operate at 16 MHz, two color LEDs directly connected to output pins provide low level debugging and status output, several components provide separate 5.0 and 3.3 V supply lines for the processor and accelerometer, respectively, and translate signal between the two levels.

The controller's two built-in UART ports are used for communication on the Soldercube assembly's global communication bus and for communication with the motor controller PCB respectively. The communication bus connecting all Soldercubes in an assembly is a one-wire bus, meaning that all modules transmit and receive on the same line. This necessitates that before any transmission commences it is checked that the line is currently not in use. In addition, the communication protocol uses simple checksums to validate correct message transmission. A global communication bus inherently limits the amount of data that can be transmitted, and by extension the number of modules connected to the bus. However, the difference in time scale between signal transmission and physical actuation places this limit in the order of thousands of modules: At the data rate of $56.6\,\text{kbit}\,\text{s}^{-1}$ used in Soldercubes, the transmission of a single 20 bit move instruction to a module takes 355 µs, while executing the movement takes on the order of seconds.

Communication between the main controller and the servo motor controller PCB is on a similar one-wire bus, but with only two participants who follow a strict server (module controller) client (servo controller) relationship. For both lines a three-state line driver integrated circuit is used to connect and disconnect the transmit and receive lines of both ports as appropriate in order to only connect the transmit pin of the UART port when sending data.

3.6 Energy module

The inclusion of an energy module type into the Soldercube system was motivated by both conceptual fit and practical utility: Conceptually, a dedicated energy storage module enables visual demonstration of the flow of energy through a network of interacting entities, a feature that is normally hidden in engineered systems. The practical use for an energy module arises because short interruptions of the power supply can easily occur when experimenting with large numbers of Soldercubes prototypes, for example due to fluctuations in the supply voltage when a single module in the assembly has an electronic failure, or when soldered connections break as a result of executing invalid robot behaviors. An energy module that can provide power to other modules in the Soldercube robot is a convenient way to mitigate this problem.

The choice of energy storage device for the energy module is limited by the actuation module actuator's voltage requirement of 12 V, the power requirement of the soldering connector of 6.6 W, and the space available inside the module. Three RCR123A package lithium iron phosphate ($LiFePO_4$) rechargeable batteries connected in series satisfy these requirements. Each cell is specified to supply up to 0.5 A of current and the nominal voltage of each cell is 3.2 V, but cells can safely be charged until the voltage reaches 4.0 V. Further benefits of the $LiFePO_4$ battery chemistry are the thermal stability, even when used incorrectly, and the easy to control characteristics of the charging process.

To keep the shape-homogenous property of the Soldercube system, the external shape of the energy module is identical to the actuator module. Internally, the gearbox assembly, slip ring and bearing are removed and the freed up space is taken up by the battery cells. Because off-the-shelf battery holders are too large to fit into the Soldercube module, two energy module specific PCBs electrically connect the batteries to the main controller PCB and the power supply line of the Soldercube assembly. These spring loaded battery holder PCBs are clamped into place when the two parts of the module shell are fastened together. In addition, one of the two battery holder PCBs acts as a battery charge controller using a circuit built around the Texas Instruments BQ24105 integrated circuit (IC) charge controller. The IC is configured to provide a 310 mA maximal charging current, and terminates the charge once the charging current drops below 30 mA. In the current design no charge termination hysteresis is configured which reduces the component count at the expense of frequent switching between charging and not charging states around the time of reaching a full charge.

In an isolated energy module not connected to a Soldercube assembly, the charge controller operates in a fashion identical to most electronic equipment with internal battery charging functionality: The batteries power all internal components of the module while disconnected from a power supply, and are charged when power is supplied externally at a voltage that exceeds the current battery voltage. What differentiates Soldercubes from the common use case of rechargeable electronics is that in a MR multiple energy modules that might be at different charge levels can be connected to the same power supply line and one should not charge another. This requirement is addressed by introducing a 0.5 V voltage drop between the positive battery terminal and the power supply line, effectively allowing for an equal difference in voltage level between any pair of energy modules.

A practical consideration for working with energy modules is that they require an externally accessible off switch as otherwise the batteries would continuously power the module even when no experiment is performed. This switch is embedded in the smaller part of the module shell. When in

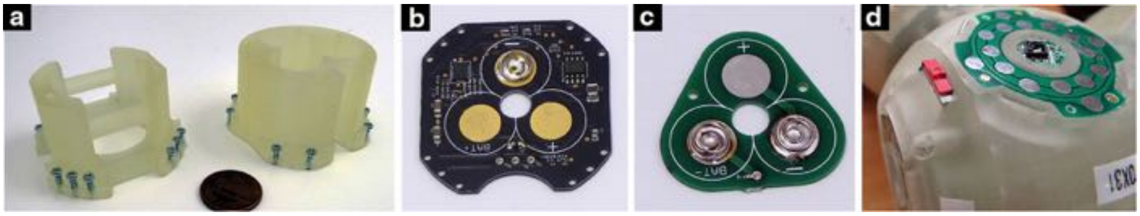

Fig. 5 Structural and Energy module components: **a** Internal structure of structural module (*left*) and energy module (*right*) with US penny as scale reference. **b** Battery charging control PCB including battery connectors for battery holder. **c** Second part of battery holder. **d** Exterior of energy module with battery switch

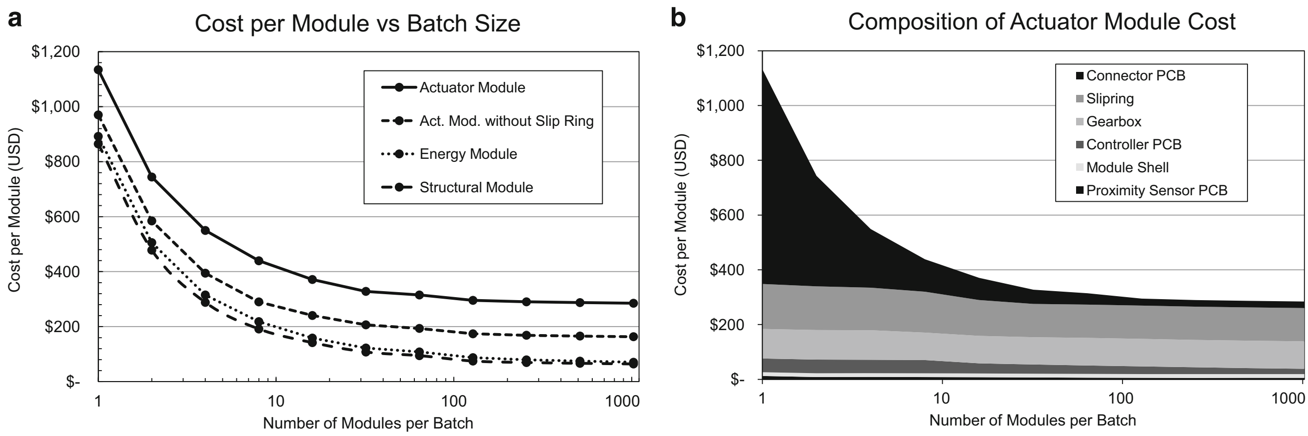

Fig. 6 Cost of module types for various batch sizes in USD. **a** Based on published price information, vendor quotes, and fabrication cost estimates, the component cost for manufacturing various batch sizes of Soldercube modules was estimated. Assembly is not included. **b** The cost breakdown for the Soldercube actuation module illustrates the effect of designing the connector for mass-manufacturability. At the lower end of batch size, module cost is dominated by the minimal order cost of custom fabricated components. At the high end of the batch size range shown here, a small number of high-price components dominate the price per module such as the slip ring and the bearing

the off position, the energy module is functionally equivalent to the passive structural module.

The total weight of the energy module is 138 g, including batteries, making it only marginally heavier than the actuation module. Its component cost is USD 108 of which USD 40 account for energy module specific components. An exploded view of the energy module is included in Fig. 4. The battery cells with battery holder PCBs with charger are shown in Fig. 5a–c, and Fig. 5d shows the externally accessible slide switch for disconnecting the battery.

3.7 Cost

Figure 6a shows the estimated cost per module for a selection of batch sizes ranging from an individual module to 1000 modules. Cost estimates are computed directly from the bill of materials accounting for all purchased parts and fabrication, but not assembly labor. All underlying component price information is sourced from the same vendors from whom parts were purchased for the construction of Soldercube prototypes.[4] As a result, the price estimates represent realistic final cost for batch sizes up to hundreds of modules, while the cost of larger batches might overestimate the true cost achievable through alternative sourcing strategies or custom manufacturing of high cost components. For components for which the full price matrix is not available, a conservative estimate of the price breaks was made based on vendor quotes. Cost estimates of 3D-printed parts assume a cost of USD 0.43 per cm^3 of component volume, based on the cost of Objet Fullcure720™ material and assuming that an identical amount of Fullcure705™ support material is consumed for part fabrication. For PCB fabrication cost the lowest quoted price from two suppliers, offering low cost small run and general purpose medium run fabrication, respectively, was assumed.

A breakdown of cost per subassembly of the Soldercube actuation module is shown in Fig. 6b. As is common for MR systems, the actuated degree of freedom and connection method are the main contributors to total module cost. While the cost for the drive system (grouped as subassemblies "gearbox" and "slip ring") remains approximately constant for all batch sizes, the cost of the connectors exhibits characteristics of a mass-manufactured component: At small batch sizes the cost of the connector is dominated by the minimal order cost of custom fabricated components, but drops by an

[4] Full bills of materials including vendor information for all components are available from the Soldercubes project website.

order of magnitude for larger batch sizes. With the sourcing methods explored so far, above module batch sizes of 500 (3000 connectors) the cost for all six connectors in a module is USD 24.

4 Experiments

With the module design for actuator, structural, and energy modules finalized, we constructed a total of 40 Soldercube modules (including 13 actuator modules and 3 energy modules). The following sections describe a series of experiments, each utilizing a subset of our module library and designed to demonstrate a specific subset of functionality required for self-reconfiguring MR modules.

4.1 Basic pair

A pair of an actuation module and an energy module is enough to demonstrate the basic functions of an autonomous robot: sensing, computation, and actuation. For this experiment an actuation module with its axis of rotation vertically oriented is attached on top of an energy module. With the energy module resting on the ground, four of its adjacency sensors are accessible. The software of the actuation module is unmodified from the standard described above in Sect. 3.5, while the functionality of the energy module is extended by the following behavior:

- When the north[5] facing adjacency sensor is obstructed, *command mode* is activated for five seconds and the LED is steady red.
- When the *east* facing adjacency sensor is obstructed while in command mode, a rotation command is sent to the attached actuation module to trigger a 90° *clockwise* rotation.
- When the *west* facing adjacency sensor is obstructed while in command mode, a rotation command is sent to the attached actuation module to trigger a 90° *counter-clockwise* rotation.
- When the north, east, south, and west facing adjacency sensors are obstructed concurrently, the top facing connector is heated in order to attach or release the actuation module.

The interaction with the basic pair assembly is shown in Fig. 7 as a sequence of photographs and as a video on the project website. This simple experiment validates the fundamental functionality required of every module in a homogenous MR system, namely actuation, control and sensing. In addition, this experiment also acts as a proof of concept for energy storage and distribution, as well as communication between modules–requirements for modules to interact in an assembly to form a MR.

4.2 Assembly substrate

Before proceeding to describe more advanced experiments, the tiled assembly substrate on which all following experiments are performed shall be described. The substrate consists of tiles that are patterned at an interval of the same 55 mm length as the length of a lattice cell. Each substrate tile contains a soldering connector identical to those in the Soldercube modules, making the substrate functionally equivalent to a layer of assembled modules. The purpose of the lattice is to enforce the constraint that all Soldercube modules in a system are aligned with a 3D grid when interacting. In addition, each substrate tile is connected to the shared power supply and ground lines in order to enable its soldering connector function and to transmit power to any attached module. The Soldercube communication bus is also connected to all substrate tiles. This has the effect that all Soldercubes directly or indirectly connected to the substrate form one system with one shared communication bus.

The experiments described in the following section are performed on a substrate where each tile's soldering connector's control signal is connected to a PC digital output peripheral and controlled manually from a simple graphical user interface. Each substrate tile's soldering connector can form and break connections independently of all other substrate tiles and modules and does not require the presence of a communication bus to do so. For ease of setup, only the required subset of tiles is electrically connected and populated with soldering connectors in each experiment.

Section 5 will introduce extensions to the Soldercube module design allowing for operation of Soldercubes robots outside the lattice framework and away from an assembly substrate.

4.3 Connection and disconnection

The acquisition and rejection of modules from a MR without external manipulation is a key component of behaviors that include interactions with the environment. The sequence shown in Fig. 8 is a basic demonstration of the capability of Soldercube modules to form and break connections between modules autonomously, as well as the ability to incorporate modules acquired from the environment into an existing robot. In this experiment a free module is first acquired by a four-module robot through actuation and forming a connection, and subsequently released. This experiment is described in detail in Neubert et al. (2014). There, we include quantitative results on the repeatability and mechanical strength of

[5] In this section, compass directions are used to describe relative orientation.

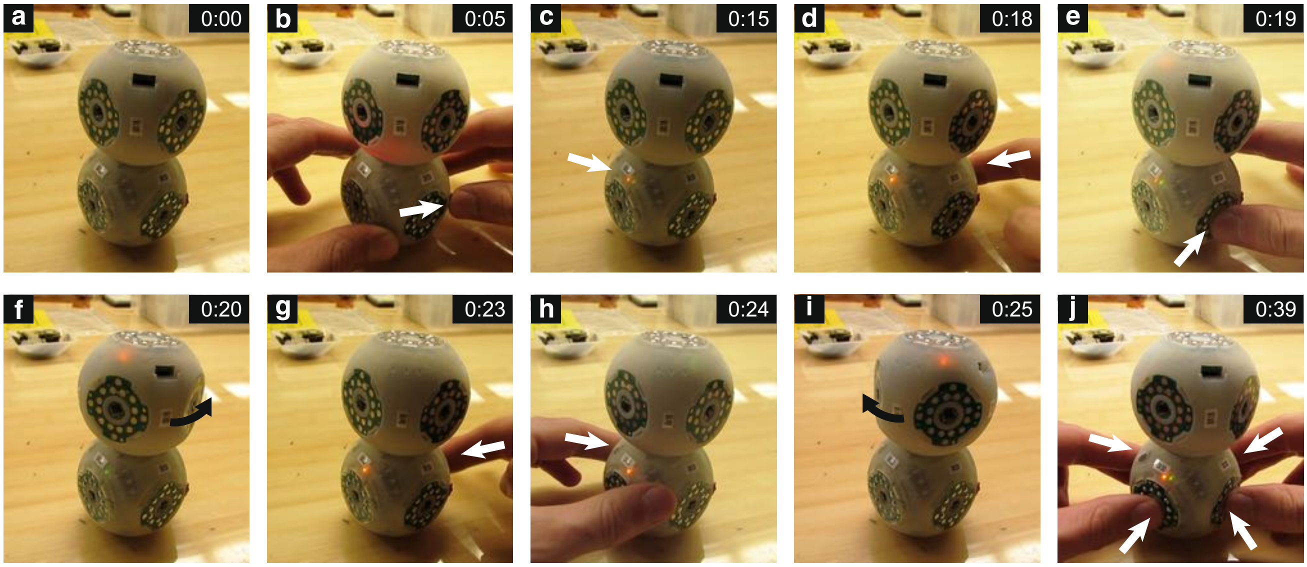

Fig. 7 Basic pair experiment (sequence with timestamps): **a** An energy module with modified control software (*bottom*) is connected to an actuation module (*top*). **b** The energy module is switched on (*arrow*). **c** Indicator lights (*arrow*) indicate that both modules are powered. **d** Touching the energy module's *north* facing adjacency sensor (*arrow*) enables command mode, as indicated by a steady red indicator LED. **d** Subsequently touching the *west* facing adjacency sensor (*arrow*) triggers the energy module to send a rotation instruction to the actuation module and **e** the actuation module rotates 90° counter-clockwise (*arrow*). **f** Command mode is entered again by touching the *north* facing adjacency sensor (*arrow*) and **g** another rotation instruction is triggered by touching the *east* facing adjacency sensor (*arrow*), **h** causing the actuation module to rotate 90° clockwise (*arrow*). **i** Touching all four accessible adjacency sensors (*arrows*) of the energy module at the same time triggers the energy module's soldering connector to heat, which allows for manually disconnecting the actuation module

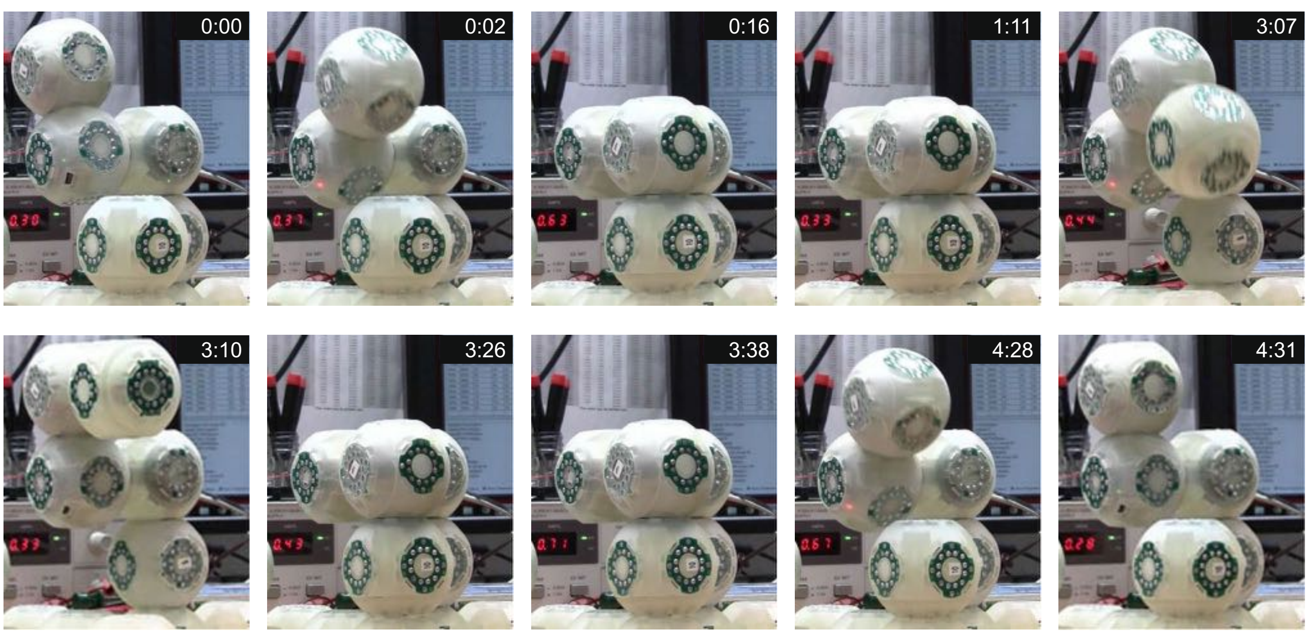

Fig. 8 Module acquisition and rejection (sequence with timestamps): A four-module Soldercube assembly (*back*) with one actuated module is actuated to occupy a lattice cell adjacent to an unconnected module (*front*). After a heating cycle the formerly unconnected module has become part of the structure. Subsequently (*bottom row*), the sequence of actions is reversed and through repeated activation of the soldering connector heaters, the connection can be broken. This experiment is described in detail in Neubert et al. (2014)

the soldering connection method as evaluated in experiments emulating the connection cycles a connector would encounter during a MR reconfiguration scenario. These experiments indicate that the soldered connection supports tens to hundreds of connection cycles and fails at tensile loads exceeding the weight of 50 actuated Soldercubes.

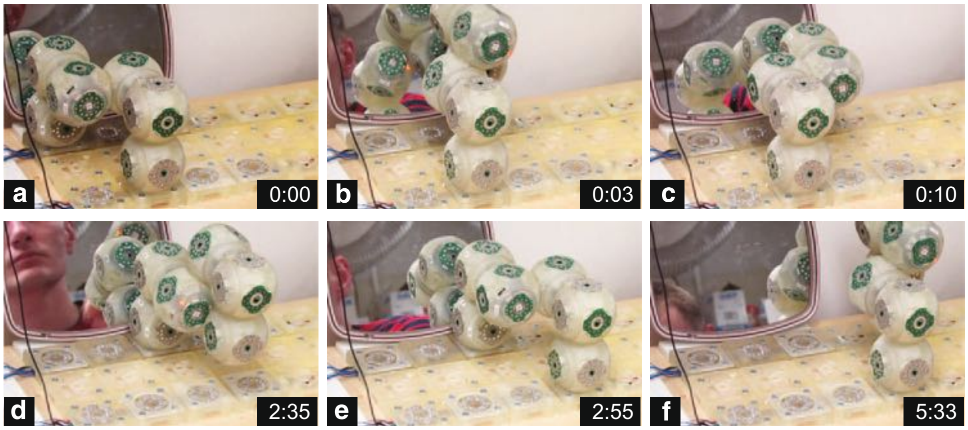

Fig. 9 Simple walker (sequence with timestamps). A robot consisting of two actuation modules and four structural modules moves over the substrate. **a** The *far left* substrate tile is heated and **b** the robot's *left* leg's actuation modules move it two lattice cells forward. **c** After the step the substrate tile's heater is activated and subsequently let cool to form a soldered connection between the robot's left leg and the substrate. **d–f** The same protocol is repeated for the *right* leg and *left* leg

4.4 Simple walker

For many meaningful interactions between a robot and its environment, the robot must be able to move within its environment. The Soldercubes system requires at least two actuation modules within an assembly for locomotion to be possible. Figure 9 shows a "simple walker" taking three consecutive steps on the substrate. The simple walker is a two legged robot consisting of a "body" with two actuation modules and two "legs" with two structural modules each. Walking over the substrate can be achieved by repeatedly performing the following sequence of interactions (yielding two steps):

1. Create a soldered bond between the right lower structural module and the substrate.
2. Actuate the left actuation module to turn 180° in the positive direction, and the right actuation module to turn the same distance in the negative direction, causing the right half of the robot to move forward by two lattice cells.
3. Create a soldered bond between the left lower structural module and the substrate.
4. Heat the soldered bond between the right lower structural module and the substrate in preparation for disconnecting.
5. Repeat the actuation pattern step 2. With the changed connection topology, this now result in the right half of the robot disconnecting from the substrate and moving forward by two lattice cells.

In addition to demonstrating the ability of Soldercube assemblies to locomote, this demonstration confirms that the soldering connection method withstands sufficiently large forces to allow for cantilevered loads and realistic operation of module assemblies. Due to insufficient precision in motor control resulting in gaps and offsets of up to 2 mm, performing the sequence of three steps as shown in Fig. 9 required manual intervention for alignment of modules with the substrate. The same root cause also led to poor alignment between adjacent connectors before forming a connection, leading to reduced reliability and mechanical strength of the connection compared to the results of our experiments with the connectors in isolation. As a result, our most immediate plan for further improvements to the Soldercube module design is to replace the difficult to control Dynamixel servo motor package with a DC motor directly controlled on the Soldercube main controller.

4.5 Synchronized motion

Once multiple actuator modules are present in an assembly, timing of actuation operations becomes important. Poorly synchronized motions might otherwise result in collisions or movements that introduce stress into the assembled structure potentially resulting in mechanical failure of the MR. The sequence of photographs in Fig. 10 shows one component of a four legged gait implemented on a 21 module Soldercube MR. During this step, the central "torso" of the structure is moved two lattice cells forward by actuating all eight actuated modules in the robot's legs synchronously. The Soldercubes system uses a combination of buffered, interrupt, and broadcasting messages to successfully implement synchronized motions as shown in Fig. 10:

1. Buffered messages allow for sending individual actuation commands to a series of cubes sequentially,

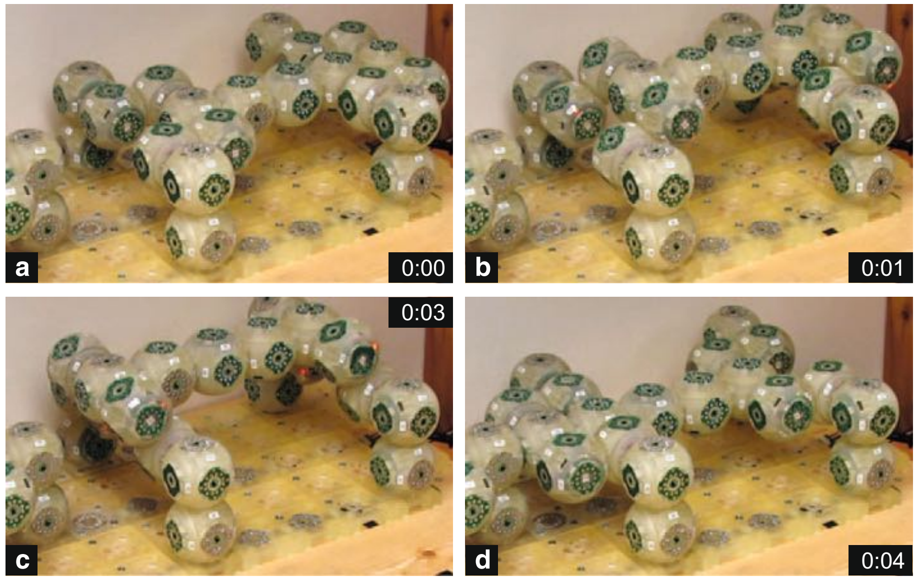

Fig. 10 Synchronized motion (sequence with timestamps). **a**–**d** A Soldercube assembly consisting of four "legs" with two structural and two actuator modules each and a "body" consisting of four structural and one energy module is actuated to move the body two lattice cells forward while all legs remain connected to the substrate. This motion requires precise timing between all eight actuator modules in the structure

with the actuation delayed until a separate trigger is received.

2. Interrupt messages interrupt the normal event loop of the module controller resulting in predictable and fast response to incoming triggers.
3. Broadcast messages directed to a reserved address are processed by all modules and serve as a trigger for the execution of previously buffered messages simultaneously in all modules.

The combination of these three message types allows for nearly synchronous actuation in an assembly consisting of many cubes communicating on a single communication bus. For the operation shown in Fig. 10 a total of 17 messages must be sent, 16 of which result in an acknowledge response to the sender. The single possible cause of incorrect actuation is therefore non-receipt of the broadcast message following successful transmission of 16 other messages.

A flaw in the integration of the soldering connector into the Soldercube module is exposed by this experiment: Because the Field's Alloy menisci partially protrude past the nominal lattice cell boundary, unintended electrical contact can occur when modules slide past each other in directly neighboring cells. For the purpose of this experiment, this problem was overcome by disconnecting the affected soldering connectors from their respective module's main controller. Permanent solutions include a self-retracting connector mounting where permanent magnets only bring two neighboring connectors into physical contact when they are aligned, and electronically disconnecting the power supply from connectors when no connection is present or currently being formed. Neither feature is currently supported by the current Soldercube design.

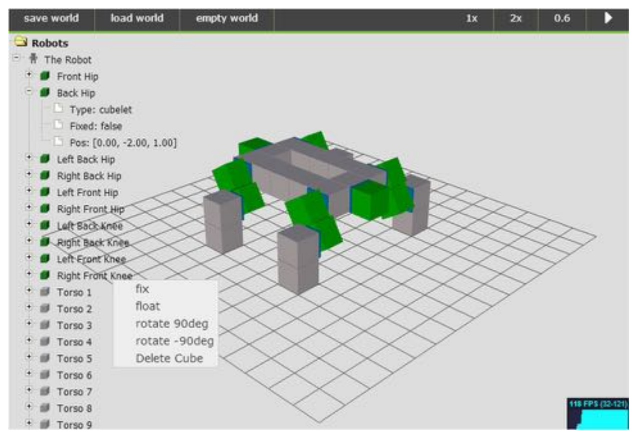

Fig. 11 Graphical user interface for simulation of MR assemblies. A 3D visualization of a predefined scenario consisting of module locations and connectivity and individual module actions can be played and edited in a web browser based graphical user interface. Here, an experimental setup similar to that in Sect. 4.5 is simulated with actuator modules shown in *green* and structural modules in *grey* (Color figure online)

4.6 Future work

The experiments described in previous sections establish the feasibility of the Soldercubes system as a platform for modular self-reconfiguration experiments in a lattice configuration. We have already assembled a total of 40 Soldercubes with the goal of creating scenarios with increasing numbers of modules. This will go alongside increasing the level of automation in the control of the Soldercube assemblies. Our browser-based simulation and 3D visualization tool for lattice based MR, shown in Fig. 11, is our primary tool for developing scenarios to be implemented in future experiments.

5 Hardware design extensions

While the experiments in Sect. 4 require a substrate and place modules in a three-dimensional grid, the Soldercubes system is readily extended to support other scenarios. In the course of our experimental work with the Soldercubes system, we developed several proof-of-concept demonstrations for possible system extensions, three of which are briefly presented here.

5.1 Towards untethered operation: WiFi module

In all experiments with Soldercubes described so far, all modules are physically connected to a common communication bus through other modules or the substrate. Many applications do, however, require the operation of various system parts in locations that are not on a joint substrate. Even when operating in close proximity, the creation of a continuous substrate might be prohibitively costly or invasive.

The WiFi connectivity Soldercube module extends the structural module to house an electricimp^{TM} wireless network node. The electricimp is a fully integrated IEEE802.11 WiFi node including an antenna and a programmable microcontroller (Electricimp 2013). Each electricimp connects directly to an internet server through which the node is globally uniquely addressable. The initial connection setup with the local wireless network is through a process named “blinkup” whereby the access credentials are transmitted optically through a flashing smartphone screen to a photodiode.

Using the space and communication lines otherwise occupied by the servo motor, the electricimp module acts as a splitter in the Soldercube communication bus. All data received from other modules is relayed to the electricimp, while all data received from the electricimp is re-broadcast to the module assembly. The server side “agent” for each WiFi module is programmed to forward messages to all other registered agents allowing for experiments with arbitrary numbers of WiFi modules. The demonstration of the Soldercube wheel module described below and shown in Fig. 13 uses this wireless bridge to control the car assembly wirelessly from a graphical user interface.

5.2 Towards inter-robot communication: Light module

The light module is a structural module that houses a high brightness RGB color LED. The module, shown in Fig. 12, re-purposes the microcontroller pins reserved for communication with the servo motor controller PCB in the actuation module for generating three pulse-width modulated control outputs to set the LED’s color. Power is drawn directly from the 12 V power supply line. The embedded software in the module controller and the communication protocol were extended by one additional command type to request arbitrary colors and brightness values from a light module.

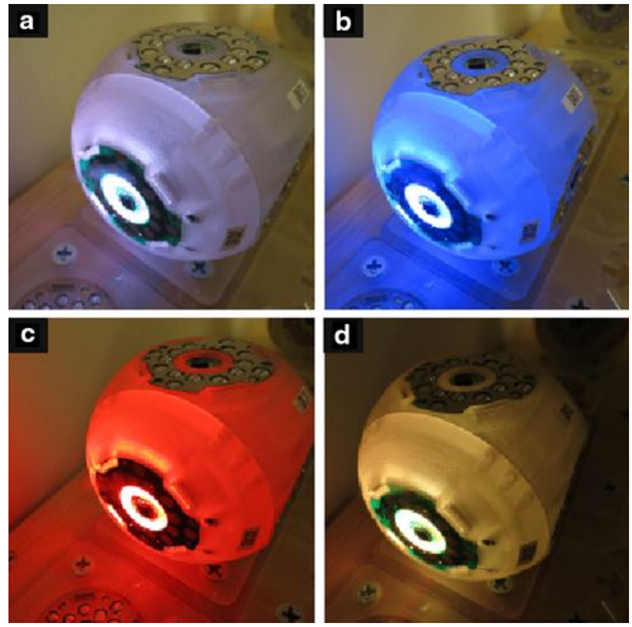

Fig. 12 LED Light Module. Instead of an actuator, this module type contains a high brightness color LED, shown here while set to **a** *purple*, **b** *blue*, **c** *red*, **d** *yellow*. Currently this module only serves as an aide to communicate robot state to the experimenter, but in future work it could be a channel for communication between Soldercubes robots (Color figure online)

The light module was initially developed as a debugging tool to communicate robot state to the experimenter when the other communication channel breaks. In combination with a yet do be developed camera or light sensor module the light module could also provide a low bandwidth channel for inter-robot communication that is separate from the Soldercubes communication bus. This conceptually mirrors organisms in nature where communication internal to an organism uses higher bandwidth communication channels than communication between organisms. Demonstrations in swarm robotics and with other MR systems have shown that simple light based systems can be sufficient for multiple robots to exhibit emergent cooperative behaviors. Examples for such beacon applications of light emitting robot modules are the use for self-assembly of swarm robots by Gross et al. (2006) and for robot localization and alignment as demonstrated with CKBot by Yim et al. (2007b).

5.3 Towards analog environments: Wheel module

Few real-world applications of MR operate in a three-dimensional grid. Existing MR toys and hypothetical search

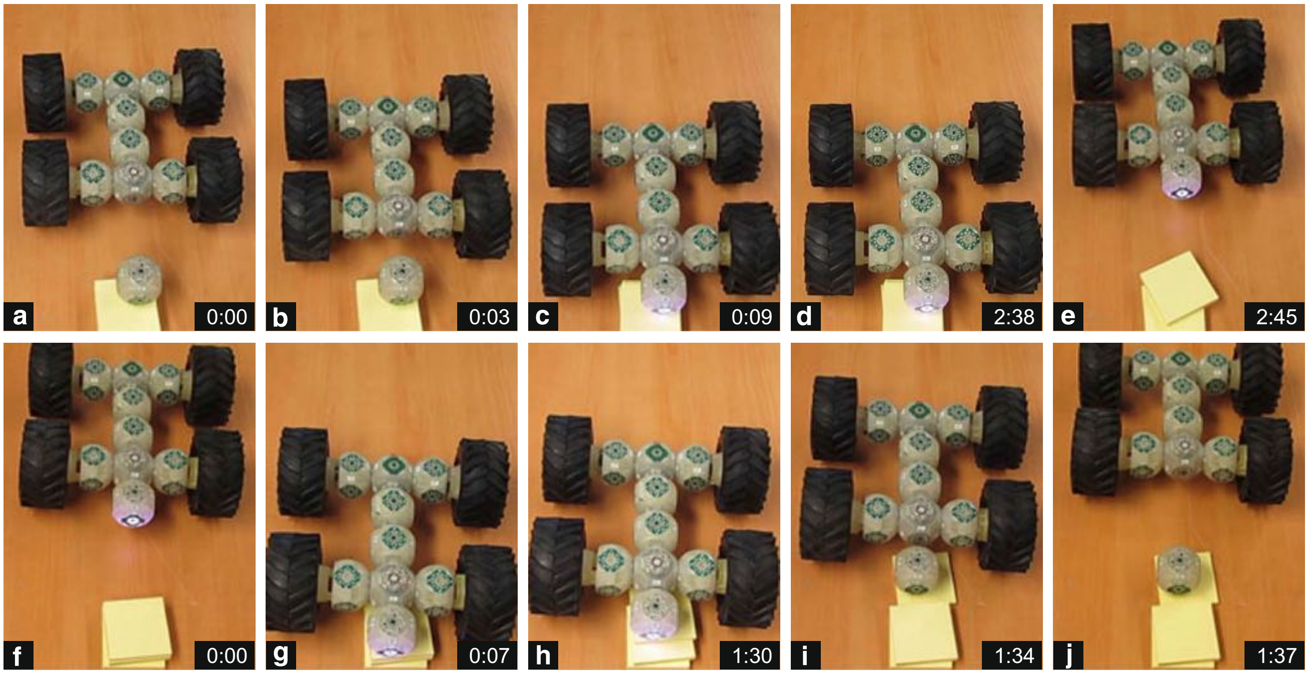

Fig. 13 Car Headlight Demonstration (sequence with timestamps). **a**–**b** A wheeled robot consisting of two structural modules, one energy module, one WiFi module and four wheel modules moves untethered. **c**–**e** A light module is acquired from the environment, and later returned through disconnection **f**–**j**. Through the addition of a continuous rotation wheel module, the lattice-type MR system has been converted into a mobile MR system that operates outside a lattice grid, exchanging modules with its environment

and rescue applications require modules to be arbitrarily placed in unstructured environments, away from a regular substrate. Implementing a wheel module converts the lattice type Soldercubes system that operates in a discretized world, as described in this paper until here, into a mobile MR that operates in a continuous environment.

To demonstrate the resulting mobile MR, a car structure was assembled with four wheel modules and a "body" consisting of one energy module, one WiFi module, and two structural modules. The MR moves on a surface to a single light module placed in the environment. By heating its appropriate soldering connector while adjacent to the LED module, the car robot acquires the LED module from the environment. As soon as the electrical connection to the newly acquired module is established the LED module initializes into a default state emitting blue light. Control of the newly acquired module is possible from any other cube or by facilitating the Wifi module's function. In this experiment, the GUI is used to send alternating commands to the light module at regular intervals resulting in flashing. This experiment is shown in Fig. 13 and in a video available on the project website.

Using the small set of hardware design extensions introduced here, this experiment demonstrates that all functions of the Soldercube system including self-reconfiguration and acquisition of modules from the environment are not fundamentally constrained to operation in a lattice type MR.

6 Discussion

The work on the Soldercubes MR system started with the recognition that the promises of versatile, robust, low-cost modular robots might be achievable through reducing cost and complexity of modules. We identified the connection method as a driver of complexity in modular robots and developed the soldering connector described in Neubert et al. (2014). The Soldercubes MR system is the application of this connector to modular robotics, resulting in the smallest, lightest, and lowest cost actuated module for a self-reconfiguring MR to date. There is, however, still a long way to go before a self-reconfiguring MR system achieves the scale at which the promises of modular robotics are realized.

6.1 Future work I: Improvements

Several design flaws of the current Soldercubes system have been pointed out in Sect. 4 and need to be addressed before Soldercubes can reliably be employed in use cases with tens of modules. The accuracy and repeatability of the rotational actuation is currently not sufficient for fully automatic operation and requires frequent manual intervention. We expect that this can be addressed with a careful iteration on the current drive system, specifically the selection of alternative materials for mounting of the potentiometer sensor and the migration of motor control from a proprietary stand-alone circuit into the main controller. The problem of unintentional electric contact between soldering connectors that slide past each other during assembly operation can be overcome by placing the constraint on assembly designs that such motion may not occur. Alternatively, connectors could be electronically disconnected while moving past other modules, or mechanically mounted to retract unless connected. Finally, a connector pad layout with fewer connector pads and a smaller cross-sectional area of solder joints is possible at the expense of reduced redundancy for electrical connections between modules.

6.2 Future work II: A mass-manufactured module

Our efforts towards optimizing the module design for mass-manufacturing techniques has been focused on the connector alone, because the connector has been the primary source of complexity in previous MR systems. The soldering connector achieves an orders-of-magnitude reduction in volume, weight, and cost when compared to other MR connectors. However, similar optimizations are likely possible for other aspects of the module.

The Soldercube actuator and drive system are currently built around components of a general purpose off-the-shelf servo actuator unit. Designing an actuator and drive system specifically for the Soldercube module would likely result in cost savings because only a subset of this product's components are used, as well as through integration of the separate motor controller PCB into the Soldercube's main controller, and by sourcing servo components directly. Further, the assembly process of the Soldercube module could be significantly simplified, both because disassembly and modification of the off-the-shelf actuator is no longer required and because component selection could be optimized towards ease for assembly.

The shell and passive parts of the Soldercube module are currently 3D-printed due to the ease of prototyping and small number of design constraints this manufacturing process has. It is likely that the majority of passive components in the Soldercube module can be either injection molded or CNC machined after the mechanical design of these components has been revised with the constraints of the respective process in mind. At scale, both processes would allow for orders of magnitude in cost savings over the current component cost which remains constant for all batch sizes due to the nature of the 3D-printing process. Finally, the integration of all PCBs into a single PCB with rigid and flexible sections would likely result in constant factor cost savings because the custom cable currently accounts for 81 %[6] of the cost of the soldering connector and connectors account for 6 %[7] of the cost and 13 % of the part count on the main controller PCB. While it is impossible to predict the exact price point, we estimate that through careful optimization of the design and improved sourcing strategies, a self-reconfiguring MR module equivalent in specification to the actuation Soldercube can be produced at a component cost of USD 200.

An ambitious goal for the modular robotics community would be to make a self-reconfiguring MR system as affordable as other popular open source engineering projects such as DIY 3D printers and quad-rotor drones. Further conceptual improvements akin to the change from mechanically actuated connectors to the soldering connector are required for the order of magnitude cost reduction that is necessary to make this goal a reality for a system with tens of modules.

6.3 Open source modular robotics

In this paper we suggest design for mass-manufacturability as a possible route towards realizing the promises of self-reconfiguring modular robotics. The availability of low-cost mass-produced modules, which is within reach today, has the potential to increase accessibility of the field. However, the large initial investment needed to exploit the economies of scale that enable this availability in the first place are prohibitive in the context of a research project. The Soldercubes project illustrates this at the small scale: Producing a total of 40 Soldercubes allowed the use of some processes with inherent operational efficiencies for batches, making Soldercube one of the cheapest MR modules to date. However, the low cost per module could only be achieved because 40 modules were produced at a total parts cost of USD 7000.[8] We consider this conundrum of the high cost of low cost modules the fundamental obstacle to more widespread use of MR.

Commercialization is one avenue to overcome this obstacle, and the commercial success of the aforementioned Cubelets MR system could be seen as an indication that the field of modular robotics is ripe for applications outside academic research. To facilitate this development, all design documentation of the Soldercubes project is made available under a permissive open source license, allowing for derivative works to be used freely for commercial and non-commercial purposes.

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[6] At a batch size of 50. The fraction reduces to 55 % at batch sizes of 5000 and higher.

[7] At a batch size of 50. The fraction increases to 10 % at batch sizes of 5000 and higher.

[8] Ignoring for all costs associated design iterations and waste. Theoretical parts cost of of 12 actuated modules at USD 335, 3 energy modules at USD 151, and 25 passive modules at USD 100.

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