Evo-bots: A Simple, Stochastic Approach to Self-Assembling Artificial Organisms

Juan A. Escalera, Matthew J. Doyle, Francesco Mondada, and Roderich Groß

Abstract This paper describes an alternative path towards artificial life—one by which simple modular robots with novel hybrid motion control are used to represent artificial organisms. We outline conceptually how such a system would work, and present a partial hardware implementation. The hardware, a set of self-reconfigurable modules called the evo-bots, operates on an air table. The modules use a stop-start anchor mechanism to either rest or move. In the latter case, they undergo semi-random motion. The modules can search for, harvest and exchange energy. In addition, they can self-assemble, and thereby form compound structures. Six prototypes of the evo-bot modules were built. We experimentally demonstrate their key functions, namely hybrid motion control, energy harvesting and sharing, and simple structure formation.

1 Introduction

A long term goal of robotics is to produce not only robotic organisms, but entire robotic ecosystems. Such systems are not only a scientific curiosity in and of themselves, but could allow us to better understand the biological processes that they mimic. Although much work has been conducted on populations of virtual crea-

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tures with evolving morphology [8], [25], [23], [20], relatively few examples have been transferred into reality [3], [19]. This motivates one of the grand challenges in evolutionary robotics—to create ecosystems of physically evolving robots [9].

Fundamental to an evolving ecosystem is the ability of its members to reproduce. Jacobson [15] studied self-replicating sequences of track-bound modules. Chirikjian et al. [4] evaluated the feasibility of self-reproducing robots. Zykov et al. [27] demonstrated structured duplication using a lattice-based reconfigurable robotic system. In the Symbrion/Replicator project, a heterogeneous system of reconfigurable robots was considered [16]. The systems in these examples involved *self-propelling modules* of high complexity. While this may enable them to interact multifariously with their environments, the modules were expensive to make, limiting the number of them in practical experiment.

An alternative approach to a self-reproducing system is to use modules that require external stimulation to move. Penrose and Penrose developed a self-replicating mechanical system [21]. This was extended by Breivik [2] and Virgo et al. [24]. Griffith et al. developed self-replicating modules with programmable on-board controllers [12]. Other works with programmable modules present structure formation, but not replication [26], [17], [14]. The modules used in these examples were simple, *externally propelled devices*. While this made them relatively inexpensive to construct and therefore producible in large quantities, the modules could only interact with their environment in a limited manner.

In this paper we present the evo-bots[1], a system of reconfigurable modules that combine the advantages of the above two classes of systems. Due to being externally propelled, the evo-bot modules are mechanically simple. Yet, they can indirectly control where to move, by using stop-start mechanisms (an approach seen only in simulation [6]). In addition, they can search for, harvest and share energy, as well as self-assemble, and thereby organize into distinct morphologies.

The paper is organized as follows. Sect. 2 concerns the evo-bot concept. Here we describe how simple modular robots can potentially be used to form an artificial life system. Sect. 3 describes our hardware, inspired by the evo-bot concept. Sect. 4 presents proof-of-concept experiments, showing that our hardware implements several features of the evo-bot concept . Sect. 5 concludes the paper.

2 Evo-bots: Toward Artificial Life Systems

In nature, living beings exhibit a high degree of autonomy. Individually, they can adapt to the environment to obtain from it what they need to survive. Whilst as species, they have developed mechanisms to persist through time. These qualities should be mimicked by artificial systems to become truly autonomous.

The *evo-bots* system consists of building blocks, called *modules*, which do not move by themselves. Rather they require an external agitation apparatus, which

[1] The conceptual foundation is based on preliminary work presented in [13]. This work also presents simulation results and a preliminary module implementation (described further in [7]).

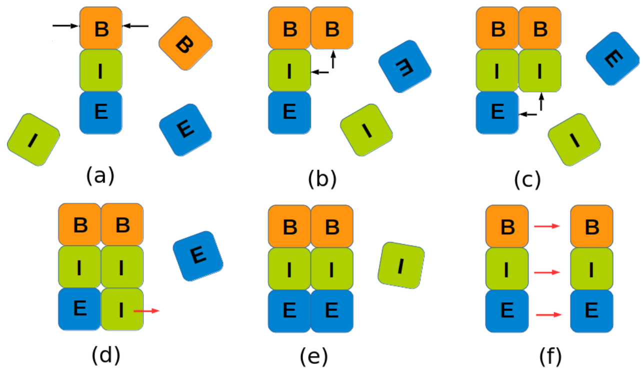

Fig. 1 Process by which an organism builds a replica of itself. (a) The organism's *b*-module activates its connectors; (b) and (c) two matching modules connect to the organism; (d) a non-matching module connects but is rejected; (e) a matching module connects; the child organism is complete and receives energy from the parent organism; (f) the parent organism repels the child organism.

causes the modules to undergo semi-random motion. The modules have a squared shape and four identical connectors—one per side. When two modules collide, they can connect to one another by chance. Once connected, they can exchange information and decide whether to remain connected. By disconnecting selectively, the modules can organize into linear composite structures called *polymers* (similar to [12]).

The evo-bot modules come in three types, each one endowed with unique functions:

- ***e*-module:** This module can harvest, store and provide energy.
- ***i*-module:** This module can interact with the environment. It can sense the environment and control its motion using a stop-start anchor mechanism.
- ***b*-module:** This module acts as a boundary, once it connects to a polymer, the latter stops growing and becomes an *organism*.

Each module assumes one of these types during each experiment. Organisms must accrete specific modules to perform specific functions. They need energy to sustain themselves. Therefore, they must contain at least one *e*-module. The *e*-modules share their energy with any module that is part of their compound structure. If the energy within a structure is depleted, the structure will decompose into its constituent modules.

Once a polymer accretes a *b*-module and becomes a complete organism, it can begin to replicate itself using free modules in the environment. This process is illustrated in Fig. 1. The replication of organisms that can sustain themselves and the decomposition of those that cannot is envisaged to give rise to populations of organisms well adapted to their environment [13]. Replication can be exact, resulting in a pair of identical organisms, or involve mutation.

Various definitions of life have been proposed [22], [5], [18]. We argue that the evo-bot concept encompasses at least one of these definitions—the seven pillars of

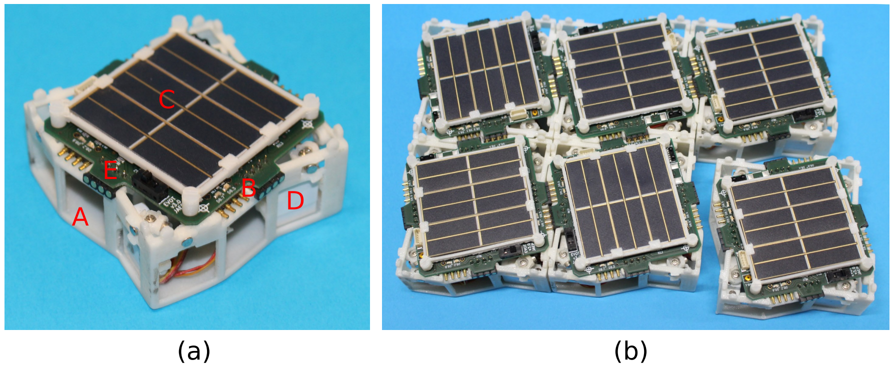

Fig. 2 (a) A single evo-bot module. (b) Six evo-bot modules, five of which are connected.

life proposed by Koshland Jr. [18] . These pillars represent attributes that an organism should exhibit in order to be considered as a living being. They are program, improvisation, compartmentalization, energy, regeneration, adaptability and seclusion. We justify our claim that the evo-bots embody this concept as follows. Each organism encodes the information of its constituent modules, their functionality and how they interact (program). The modules are able to alter said program between generations (improvisation). Each organism defines its own space, which is protected by a boundary, wherein internal processes run protected from external disturbances (compartmentalization). Organisms are able to harvest, store and distribute energy from the environment (energy). Organisms possess the capacity of self-replication (regeneration). They can vary their behavior according to external stimuli (adaptability). Finally, the information within each organism is protected from external agents (seclusion).

3 Evo-bot Hardware

This section describes the evo-bot hardware. The physical modules do not yet represent a full implementation of the evo-bot concept, but form the basis of one. Conceptually there are three different types of evo-bot modules (e, i, b). However, from a mechatronic point of view, each module is identical. Each module is configured to assume only one of these types during an experiment. This generic design allows each module to execute any of the three roles, which eases fabrication and usage.

Fig. 2a shows an evo-bot module. The overall dimensions of the module are $60 \times 60 \times 35$ mm. The module weighs 50 g. It has a 3-D printed ABS structure (Fig. 2a-A) with a 60 mm square base, which is surrounded by walls (faces) of 25 mm height. Viewed from above, the walls have a mildly serrated structure in order to engender self-alignment when modules connect.

The evo-bot modules float on an air table. They exploit this by using a motion control method suited to their environment. The module incorporates a stop-start mechanism, shown in Figs. 3a and 3b. It consists of a flanged cylinder (anchor) fitted vertically into the base of the module. The anchor contains one permanent magnet (A), and is positioned directly beneath a second magnet (B). Magnet B is rotatable by a servomotor. In the 'start' state magnet B is rotated to attract magnet A, pulling the anchor upwards, away from the air table surface. This allows the module to float freely. In the 'stop' state, magnet B is rotated to repel magnet A, thereby pushing the anchor down onto the air table. This causes friction between the module and the air table and renders the module incapable of floating, pinning it in place. The effectiveness of the anchor mechanism in a polymer depends on the configuration of the polymer itself. For instance, a single *i*-module activating its anchor may be unable to prevent translational motion of an entire organism.

Physical connection between modules is facilitated by a pair of permanent magnets in each face. One magnet per pair is fixed into the plastic wall. The other is mounted on a servomotor (Fig. 2a-D) and can be rotated in order to attract or repel another module [1].

The module can derive information about its environment by using its solar panel as a light sensor. This, in addition to the module's stop-start mechanism, allows it to interact with its environment.

A square, 52 mm printed circuit board (PCB) (Figs. 3c and 3d) is mounted on the top of the structure (Fig. 2a-E). The double-sided PCB contains the control circuitry, including the energy management system, a low power 16-bit micro-controller (the PIC24FJ128GA306) and five load switches. This provides four serial interface (UART) channels through which data can be exchanged with other modules. The micro-controller can estimate the energy balance of the module by measuring current and voltage. In addition, it can use digital outputs to switch some circuits of the module on or off.

Spring loaded contacts are mounted into each face of the PCB (Fig. 2a-B). As two modules physically connect, the contacts are brought together. This allows modules to share power and information. As shown in Fig. 4, each set of contacts passes five signals: load sharing (LS), serial transmit (TX), serial receive (RX), bus voltage (VBUS) and reference voltage (GND).

Fig. 4 shows the electrical/electronic architecture used for the module to manage energy. This is carried out by two systems: power management and energy harvesting. In the following, both systems are described in detail[2].

3.1 Power Management System

The evo-bot module uses a 300 mAh lithium ion battery to store energy. This supplies unregulated voltage from 2.7 V to 4.2 V to a high-efficient (up to 96 % effi-

[2] In [11] the authors presented preliminary work about the energy management system.

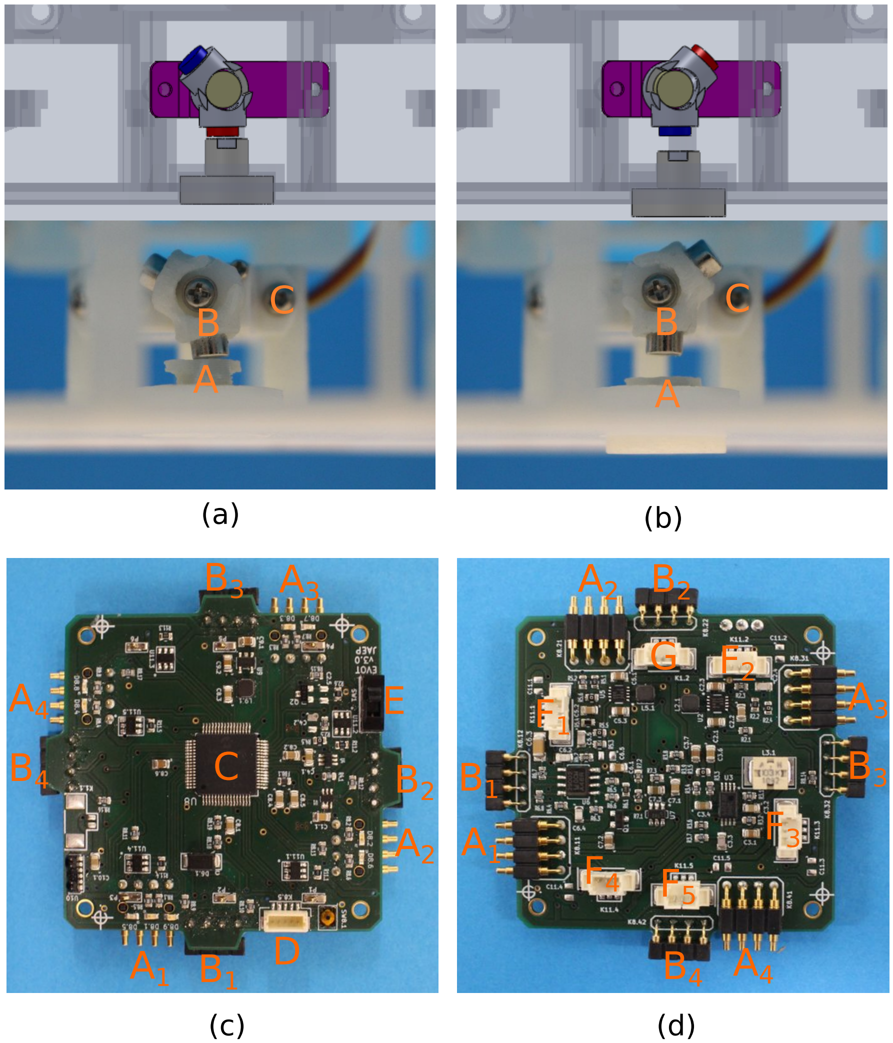

Fig. 3 (a-b) The anchor mechanism (CAD and real) showing the anchor magnet (A), the rotatable magnet (B), and the servo (C). The anchor is shown in start position (a) and stop position (b). (c-d) The top (c) and bottom (d) layers of the PCB, showing the spring-loaded connectors (A_1 to A_4), the pad connectors (B_1 to B_4), the microprocessor (C), the programming port (D), the on/off switch (E), the servo connectors (F_1 to F_5), and the battery connector (G).

ciency) buck-boost switching voltage converter that, in turn, provides 4.9 V regulated voltage output and up to 700 mA constant current. A load sharing integrated circuit (IC) varies the converter's output voltage to control the current it supplies. The output stage consists of an OR-ing circuitry that connects the regulated voltage output to the module bus voltage (line VBUS). It comprises a P-channel MOSFET

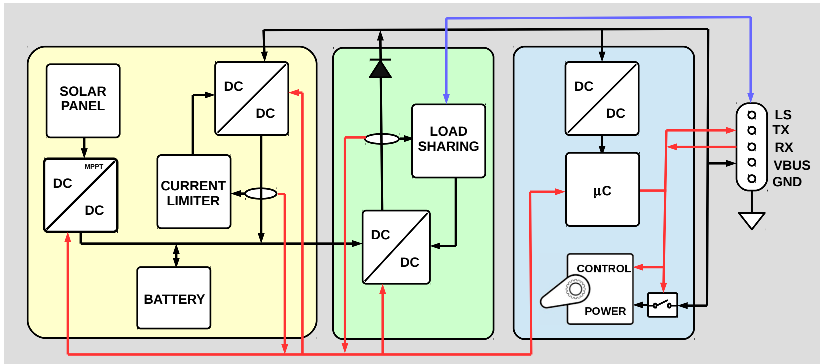

Fig. 4 Block diagram of systems within the evo-bot module. The energy management is accomplished by two systems: The energy harvesting system (yellow area) and the power management system (green area). The former comprises battery, solar charging and power bus charging. The latter includes an output voltage controlled DC/DC converter, an OR-ing diode and a load sharing IC. The remaining elements of the module (blue area) are elements for computation and actuation. The module also has four spring-loaded/pad connectors to share data and energy with other modules.

controller IC and a low resistance P-channel MOSFET, which together act as a diode with negligible losses.

If a charged *e*-module is connected with other modules, it energises them. An ad hoc controlled voltage power bus emerges through the sharing lines (VBUS) and (GND). The OR-ing circuitry preserves the integrity of the power bus formed in the polymer. Within each module, the power bus supplies two current/voltage sensors, five micro servomotors along with their switches and one micro-controller plus its additional converter (4.9 V/3.3 V).

If a polymer comprises more than one charged *e*-module among other types, power management becomes more complex as multiple regulated sources are connected to a common power line. Although such a situation may be favourable, it implies some additional elements to consider. Namely, the aforementioned OR-ing diode prevents the whole bus from collapsing if one source fails. Furthermore, it allows hot plugging. On the other hand, diodes prevent sources with different voltage levels from providing current simultaneously to the power bus. Therefore, only the highest voltage source would provide current at a time, which is undesirable. The *e*-module solves this situation by using a load sharing circuit. This circuit is placed between the converter and the OR-ing diode. The function of this circuit is to balance the current of the different *e*-modules connected through the power bus. To that end, it compares its own converter's current to that of other *e*-modules by sensing a dedicated signal (LS). This signal can be both input and output. The converter that provides the highest current sets the voltage of line (LS). The others use this information to adjust their current by adjusting the voltage of their converter until each module provides a similar current. Thus, not only do *e*-modules supply energy to other modules, but they also coordinate themselves to balance the power they supply to the bus.

3.2 Energy Harvesting System

The *e*-module uses a solar panel to obtain energy from the environment. The panel is mounted on the top of the module in a 3-D printed ABS holder (Fig. 2a-C). It consists of three photovoltaic (PV) cells (14×45 mm each) that convert radiation into electrical power. Each PV cell has an efficiency of 22 % and can harvest up to 270 mW. The output of the panel feeds a non-linear charger IC, which is connected to the module's battery. This charger, which uses the MPPT[3] algorithm, performs with an efficiency of up to 95 %. Moreover, as the battery is connected to the power management system's converter, the solar panel charger is also connected to it. Thus, the solar panel can also supply power directly to that converter.

Energy can be transferred between *e*-modules. A low energy *e*-module can provide energy to its own battery by drawing it from a high energy *e*-module through the power bus using dedicated battery charger circuitry. This circuitry integrates the same buck-boost converter as the power management system along with a current limiter circuit. As a result, a high-efficiency constant current/constant voltage charger is implemented, which is suitable for recharging lithium ion batteries.

3.3 Fabrication and Software Loading

3-D printing a set of four chassis for the evo-bot modules took 17 hours. Assembling an evo-bot module given a 3-D printed chassis and populated PCB takes 1 - 2 hours. This involves sanding the module and attaching the magnets, servo horns, servos and PV cells. The total cost to construct a single module is approximately £175, including PCB manufacture and 3-D printing costs. The evo-bot software, written in C code, is loaded onto the modules via a suitable programmer.

4 Experiments

In this section we demonstrate the key features of the evo-bots. Videos of the experiments are available [10].

The experimental environment is shown in Fig. 5 (left side). It consists of a square air table of side-length 85 cm. The surface is a 10 mm thick acrylic sheet with holes

[3] Maximum Power Point Tracking. Weak sources may collapse if they have to supply power that exceeds their limit. MPPT algorithms reach the maximum power point of a source and stay at this level. Therefore, the source supplies its maximum power in a safe way.

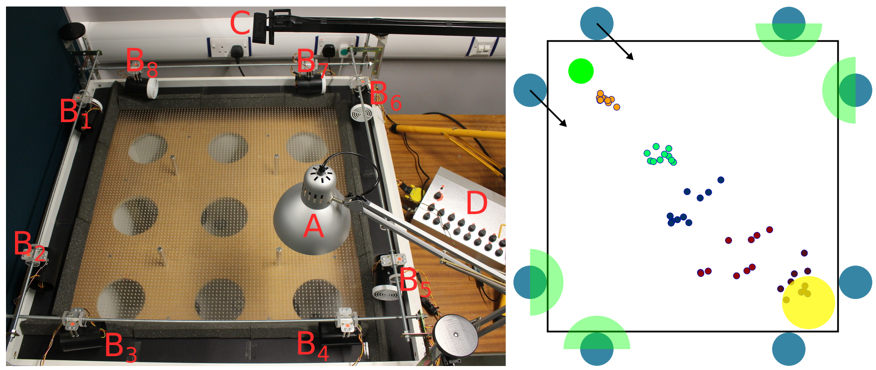

Fig. 5 Left: The evo-bot air table, showing the overhead lamp (A), the side fans (B_1 to B_8), the overhead camera (C), and the fan control box (D). Right: The light detection and motion control experiment. The side fans are indicated by large blue circles. The yellow circle in the bottom right indicates the position of the light source, and the green circle in the top left the module starting position. The colored dots represent the final positions of the modules (10 trials per color), from top left to bottom right: orange—0.3 V, teal—0.4 V, blue—0.5 V, red—0.8 V, brown—2.0 V.

drilled in a square pattern with a spacing of 10 mm. The holes have a diameter of 2.5 mm. The main upward force is supplied by four industrial air blowers positioned below the table. The environment has foam boundaries of height 30 mm, which protect the modules from damage as they contact the borders. Eight side fans (two per side) are mounted on rails around the table, pointing inwards. These supply motive forces to the modules on the air table. Each fan can rotate in the horizontal plane up to 180°. The rotation and speed of each fan can be set via a control box, which allows the fans to be activated in preset patterns throughout the experiments. An 18.5 W LED lamp with a 25° beam angle is used as the light source for the experiments unless otherwise noted. Mounted on a lamp stand it can be positioned arbitrarily over the air table. Finally, an overhead camera is used to track the modules throughout the experiments for post-analysis.

4.1 Light Detection and Motion Control

For an organism to maintain a constant supply of energy it must be able to locate an energy source. To do this, an evo-bot module must be capable of detecting whether it is located beneath an energy (light) source, and of activating its anchor mechanism to stop and charge. We test this capability here. The specific set up is shown in Fig. 5 (right). An evo-bot module was placed in the top left corner of the table. The light source was positioned 12 cm above the surface of the table in the bottom right corner, facing downwards vertically. For this experiment a bulb with a 360° beam angle was used, in order to provide a smooth light gradient over the air table. The two side fans in the top left corner were pointed in the direction of the bottom right

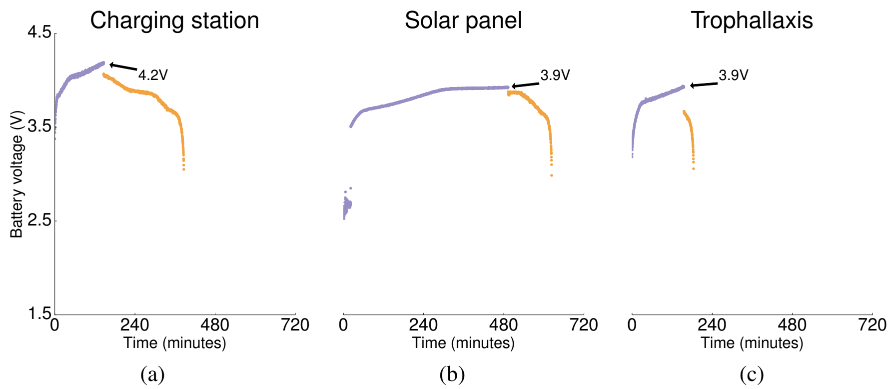

Fig. 6 Graphs showing the charging and subsequent discharging of an evo-bot module. Charging via (a) charging station, (b) solar panel, or (c) another evo-bot module.

corner. The bottom left and top right side fans were set to oscillate over a 180° range. The bottom right side fans were not used. The fans were set up in this manner in order to push the evo-bot module towards the light source. The evo-bot module was given a certain threshold for the intensity of light incident on its solar panel (determined by measuring the voltage across the PV cells). The module was blown towards the light source and deployed its anchor once the threshold was exceeded. Its final position was recorded.

We conducted 50 trials: 10 trials each for 5 different voltage thresholds. Fig. 5 (right) shows the recorded positions at the end of each trial. As can be seen, the final positions of the module are stratified depending on their thresholds—modules with higher thresholds get closer to the light source before stopping. This confirms that the module interacts with its environment as intended.

4.2 Energy Harvesting and Sharing

We examine the ability of an evo-bot module to be charged via charging station (at 4.9 V), solar panel, or another module (trophallaxis). In each case, the module started fully discharged. It was then charged for a certain period, and then discharged to evaluate its operating time. During the charging period only the micro-processor was running. During the discharging period, in addition, one servomotor was activated every 2 seconds in order to simulate the typical energy expenditure of a module during experimentation. This value was chosen based on the other experiments we conduct in this paper. However less time-sensitive experiments may not require such frequent activity, reducing energy expenditure and increasing operating time.

The charging/discharging curves are shown in Fig. 6. Via charging station the module charging period lasted until the battery was charged to 4.2V. This took

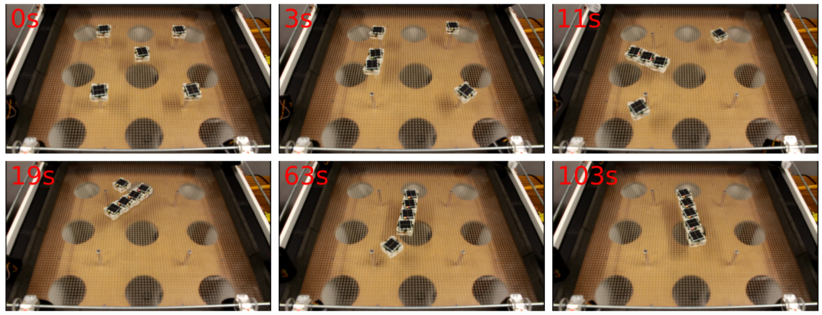

Fig. 7 A sequence of stills taken from a video of five evo-bot modules forming a linear polymer.

140 minutes, and provided 240 minutes of operating time. Due to the slow rate of charge via solar panel, charging up to 4.2 V was not feasible. Instead, the charging period was set to 500 minutes. This charged to 3.9 V and provided 120 minutes of operating time. For trophallactic charging, the donor module started fully charged (4.2 V). The receiving module was then charged by the donor module until the donor module was fully discharged. The receiving module charged to 3.9 V over 160 minutes, subsequently providing 30 minutes of operating time. An artificial ecosystem could see these charging methods combined. All organisms could feed from a limited number of charging stations, but demand would be high. Those organisms with *e*-modules would be able to locate and charge from a distribution of light sources.

4.3 Polymer Formation

We examine the ability of the evo-bots to form linear polymers. The modules were set up as follows. Individual modules were able to form a connection on any of their faces. Once a module connected to another, it refused connections with new modules on faces orthogonal to its existing connection(s). In this way only linear polymers could form permanently (other configurations could form temporarily until incorrectly attached modules were rejected). Modules periodically closed and opened their connections in order to free themselves if connected in the wrong position. At the outset of each trial four evo-bot modules were positioned at the corners of a square of side-length 34 cm, concentric with the air table. The fifth module was placed at the center of the table. The rotation of the modules was arbitrary. The modules were not given any specific type designation (*e*-module, *i*-module, *b*-module) for the purpose of this experiment.

A total of ten trials were performed. The average length of time needed to form a 5-module polymer was 188 seconds. The longest time taken was 407 seconds. The shortest time taken was 62 seconds. Fig. 7 shows stills from an example trial.

4.4 Summary

The experiments we have detailed in this section relate the evo-bot hardware to the concept discussed in Sect. 2. We have shown that the evo-bots can grow via module accretion, locate energy of various intensities, and harvest energy and share it with connected modules. These attributes represent the first stages of a hardware implementation of the evo-bot concept.

5 Conclusion

This paper described the evo-bot concept—a simple modular system that could be used to physically implement artificial life. We have shown that a potential full implementation of the concept, in which artificial organisms are capable of growing, harvesting energy and replicating, satisfies at least one definition of life. We have developed and presented a set of physical modules inspired by the evo-bot concept. While these modules do not yet represent a full implementation of the concept, they form the basis of one. The evo-bots feature a novel stop-start motion control mechanism, which requires only a single binary actuator, but allows them control over their movement. We have performed experiments with up to five prototypes to demonstrate the system's main capabilities: hybrid motion control, light sensing, energy harvesting and trophallaxis, and self-assembly. Our next aim is to introduce polymer self-replication in order to fully implement the evo-bot concept. In addition we will conduct long-term experiments involving a large number of modules.

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