Proceedings of the 2017 18th
International Conference on Advanced Robotics (ICAR)
Hong Kong, China, July 2017

Structure and Markings as Stimuli for Autonomous Construction

Michael Allwright
Department of Computer Science
Paderborn University
Paderborn, Germany
michael.allwright@upb.de

Navneet Bhalla
Department of Chemistry and Chemical Biology
Harvard University
Cambridge, MA 02138, USA
nbhalla@gmwgroup.harvard.edu

Marco Dorigo
IRIDIA
Université Libre de Bruxelles
Brussels, Belgium
mdorigo@ulb.ac.be

***Abstract*— We present a decentralized control strategy for autonomous construction that uses the structure and markings of a partially-built structure as stimuli to coordinate construction. Since this construction modifies the structure and markings of the partially-built structure, a feedback loop emerges where these modifications coordinate further construction. We demonstrate this control strategy in a physical system by designing an autonomous robot and a stigmergic block, whose hardware implementations are detailed in this paper. The work in this paper represents a milestone in our research towards the realization of a swarm robotics construction system, which aims to be capable of building a variety of structures in various settings with multiple robots.**

***Index Terms*— autonomous construction, decentralized control, stigmergy, swarm intelligence**

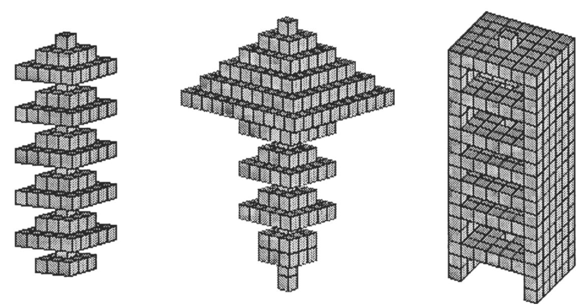

Fig. 1. Examples of the structures generated by Theraulaz and Bonabeau[1].

I. Introduction

In this paper, we present a decentralized control strategy that uses the structural arrangement of blocks in a partially-built structure and their markings as stimuli to coordinate construction. These stimuli regulate the construction behavior of an autonomous robot. Since the construction behavior of a robot results in modifications to a structure, a feedback loop emerges where construction modifies a partially-built structure, and the modifications to a partially-built structure may be used to coordinate further construction.

This approach to construction is inspired by the work of Theraulaz and Bonabeau [1], who used a similar control strategy to coordinate construction in a simulation. In their work, simulated agents performed construction in a three-dimensional lattice in response to spatial arrangements of bricks in a partially-built structure. Fig. 1 shows three structures, which were built by the simulated agents using this technique. The work by Theraulaz and Bonabeau, as well as the work presented in this paper, is inspired by the construction capabilities of social insects in nature [2].

To demonstrate that our decentralized control strategy can be realized in a physical system, we implement an autonomous construction system consisting of two components: an autonomous robot and a stigmergic block. The stigmergic blocks are a semi-active building material, which the autonomous robot can assemble into structures.

We use this hardware to verify our decentralized control strategy by having the autonomous robot perform three tasks. The first two tasks involve the manipulation of a stigmergic block with respect to a structure-based stimulus and a markings-based stimulus respectively. In the third task, we verify that both types of stimuli can be combined to coordinate the construction of a staircase.

The verification of our decentralized control strategy in a physical system represents a milestone in our research towards the realization of a swarm robotics construction system, which aims to be capable of building a variety of structures in various settings with multiple robots.

In contrast to construction systems that leverage centralized infrastructure, a swarm robotics construction system may exhibit a higher degree of fault tolerance due to the underlying decentralized control strategy. The implementation of a decentralized control strategy, however, is challenging since the mechanisms for coordinating a robot's behavior are limited to the perception of the local environment, direct communication with nearby robots, and indirect communication through the environment.

[1]Reprinted from the Journal of Theoretical Biology, Volume 177, Issue 4, Guy Theraulaz and Eric Bonabeau, "Modelling the Collective Building of Complex Architectures in Social Insects with Lattice Swarms", Pages 381–400, Copyright (1995), with permission from Elsevier.

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II. Background

In this section, we discuss the state of the art in the development of autonomous construction systems that coordinate construction using a decentralized control strategy[2].

Although recent work has demonstrated several decentralized control strategies for autonomous construction, most of the control strategies were limited to performing single pick and place operations [3], [4], or to the construction of rudimentary structures such as clusters [5]–[8], walls [9], [10], and sorted patches [11]–[14]. To the best of our knowledge, there are only three autonomous construction systems that are capable of building sophisticated structures using a completely decentralized control strategy. The following paragraphs describe each of these systems, focusing on their control strategies.

Using simulation and hardware, Jones and Matarić demonstrated a decentralized control strategy for autonomous construction [15]. Their control strategy leveraged computer vision to detect patterns of colored blocks in a partially-built structure. Upon detecting a known pattern, a robot requested the simulation engine or human operator to add another colored block to the structure. The use of a simulation engine or of a human operator, however, sidestepped significant challenges in the operation of an autonomous construction system such as locating the building material and attaching it to a structure.

Werfel et al. demonstrated TERMES, a decentralized construction system capable of building a variety of three-dimensional structures from passive tiles [16]. The control strategy for this system leveraged an offline compiler to generate a specialized map of a target structure for the robots. By entering the target structure from a predefined location, the robots tracked their location on this map as they traversed the structure and visited potential construction sites. The control strategy relied on accurate odometry, which might limit the robustness of such a construction system.

Sugawara and Doi demonstrated a decentralized construction system, which coordinated the construction of loose planar structures using semi-active blocks [17]. The control strategy was an extension of the clustering work by Deneubourg et al. [18] and used semi-active blocks to guide the robots as to where to place further blocks. The robots picked up both unused blocks and blocks that were already part of the structure. While this behavior made the structure adaptive, it limited the rate at which the construction advanced.

III. System Architecture

The decentralized control strategy presented in this paper is similar to that used by Jones and Matarić. In contrast to the work of Jones and Matarić, however, the decentralized control strategy presented in this paper is capable of coordinating three-dimensional construction and can operate without human intervention. We have implemented this decentralized control strategy using two components: an autonomous robot and stigmergic blocks, which the robot can assemble into structures (Fig. 2).

[2]We restrict our survey to autonomous construction systems that are implemented using hardware and that do not leverage any form of centralized infrastructure, such as positioning systems.

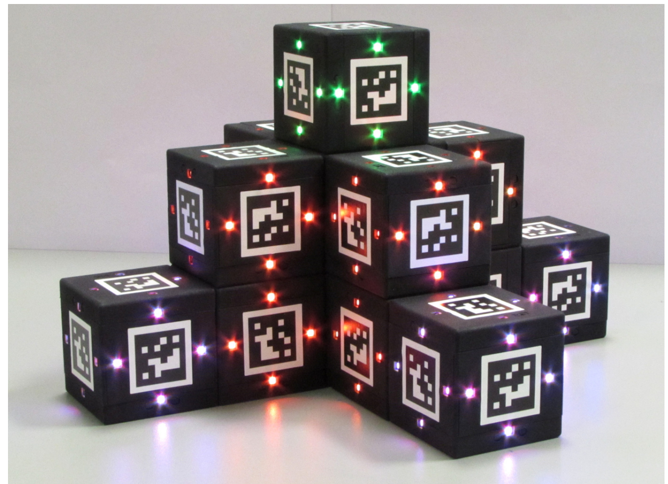


Fig. 2. A stepped pyramid made from stigmergic blocks.

A stigmergic block is an advanced cubic building material capable of computation, data storage, and communication. The enclosure of a block is printed using selective laser sintering and has a side length of 55 millimeters. To allow an autonomous robot to find a block in an environment, the faces of a block contain a localizable tag [19], whose position and orientation can be estimated using computer vision. To reduce cumulative error during construction and to increase the strength of a structure, eight freely-rotating spherical magnets are fitted into the corners of a block. A block contains four multi-color light-emitting diodes (LEDs) and a near field communication (NFC) transceiver on each of its faces. The colors of these LEDs can be configured using the NFC interface.

An autonomous robot consists of a mobile robotics platform and a specialized manipulator for assembling stigmergic blocks into structures. The robot is capable of building structures up to a height of three blocks (165 millimeters). The mobile robotics platform is a version of the BeBot [20], which we have significantly upgraded to enable on-board computer vision. The specialized manipulator attaches to the top of the mobile robotics platform and is assembled from off-the-shelf parts and components printed using stereolithography (SLA). The manipulator consists of an end-effector, which resembles a forklift mast. In contrast to a forklift mast, however, the end-effector picks up a block by attaching to its top face. The attachment is facilitated through the coupling of the four spherical magnets at the top of a block with the

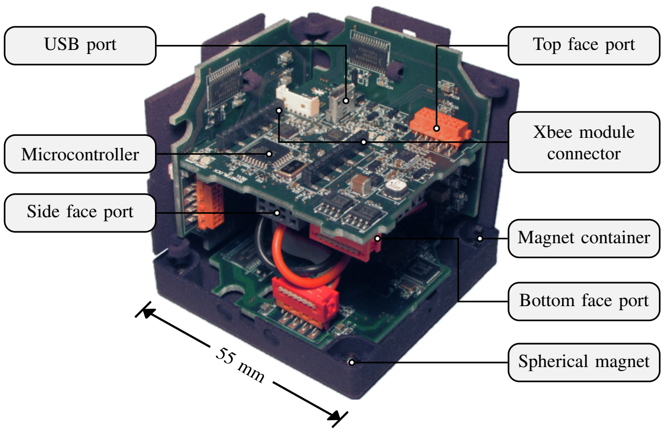


Fig. 3. Internal components of the stigmergic block.

four semi-permanent electromagnets in the end-effector. An NFC transceiver in the end-effector enables communication between the robot and a block.

Using computer vision and the NFC interface respectively, the autonomous robot can detect and configure the colors of the LEDs on a stigmergic block. These capabilities facilitate coordinated construction through a feedback loop, where the addition of a block, which is illuminated with a specific color (the markings-based stimulus), to a partially-built structure modifies the partially-built structure, which in turn coordinates further construction.

In the following sections, we provide an overview of the electronics, mechanical design, and software of the stigmergic block and the autonomous robot. For a more comprehensive report on this hardware, we refer the reader to our technical report [21].

IV. The Stigmergic Block

A. Electronics

Fig. 3 shows the internal components of a stigmergic block, including the microcontroller, which runs a block's software. The electronics of a block consist of a central circuit board and six face circuit boards. A slot for an XBee wireless module on the central circuit board enables the possibility of remote monitoring and debugging. A block is powered by a lithium-ion battery, which is recharged over a USB connection. The USB connection also provides an interface for reprogramming the microcontroller.

Each face circuit board of a stigmergic block contains a near field communication (NFC) transceiver and four multi-color LEDs. The NFC transceiver enables a block to send and receive data using any of its faces. For each face, an LED driver controls the brightness of the red, green, and blue channels of the four multi-color LEDs.

B. Mechanical Design

The mechanical structure of a stigmergic block is provided by the circuit boards and the enclosure, which is printed using selective laser sintering (SLS). The enclosure consists of a side cover, a top cover, and a bottom cover. To assemble a block, four face circuit boards are attached to four side covers using small clips. These clips are printed directly onto the cover during the SLS process. These four assemblies are then connected to the four side ports on the edges of the central circuit board.

The top and bottom covers each contain four insets for four six-millimeter spherical magnets, which are inserted and held in place using small tabs. As with the side covers, a face circuit board is attached to the top and bottom covers using a small clip. The top and bottom covers then slide over the four side covers and are held in place by small notches, which are also printed during the SLS process. A cable is used to connect the top and bottom face circuit boards to the central circuit board.

C. Software

The software for a stigmergic block is written in C++. Following initialization, a block waits for an NFC message to be received on any of its six faces. Upon receiving a message, the block uses the first byte of the received message to configure the colors of the LEDs to a given value. A valid value is a character matching '0' through '4', where '0' switches the LEDs off, and '1' through '4' configures the LEDs to one of four colors. These colors are called Q1, Q2, Q3, and Q4 and refer to the four quadrants of the UV color space. Since the images captured by a robot are in the YUV format, this selection of colors eliminates the need for a color space conversion prior to estimating an LED's color.

V. The Autonomous Robot

A. Electronics

An autonomous robot consists of a mobile robotics platform and a specialized manipulator for assembling stigmergic blocks into structures. The mobile robot platform consists of two custom designed circuit boards: the microprocessor circuit board and the power circuit board, which slot into a molded interconnect device (MID) chassis. The MID chassis consists of twelve equally-spaced range finders, which are mounted around the perimeter of the chassis. Two motors mounted to the base of the chassis form a differential drive, allowing the robot to move around its environment.

To reduce the development time and the manufacturing costs of the microprocessor circuit board, we use a Duovero Computer-on-Module (COM) from Gumstix. The COM consists of a microprocessor, which is clocked at 1 GHz and connected to 1 GB of memory. The COM also enables Wi-Fi and Bluetooth connectivity. The microprocessor on the

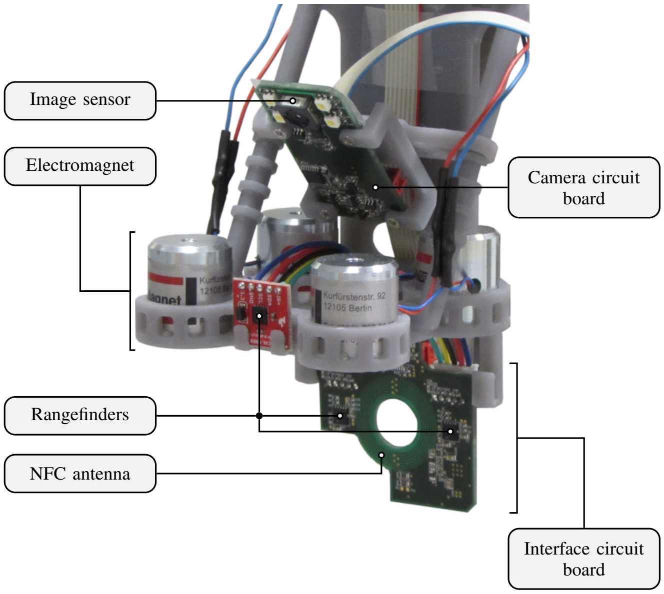


Fig. 4. The end-effector of an autonomous robot.

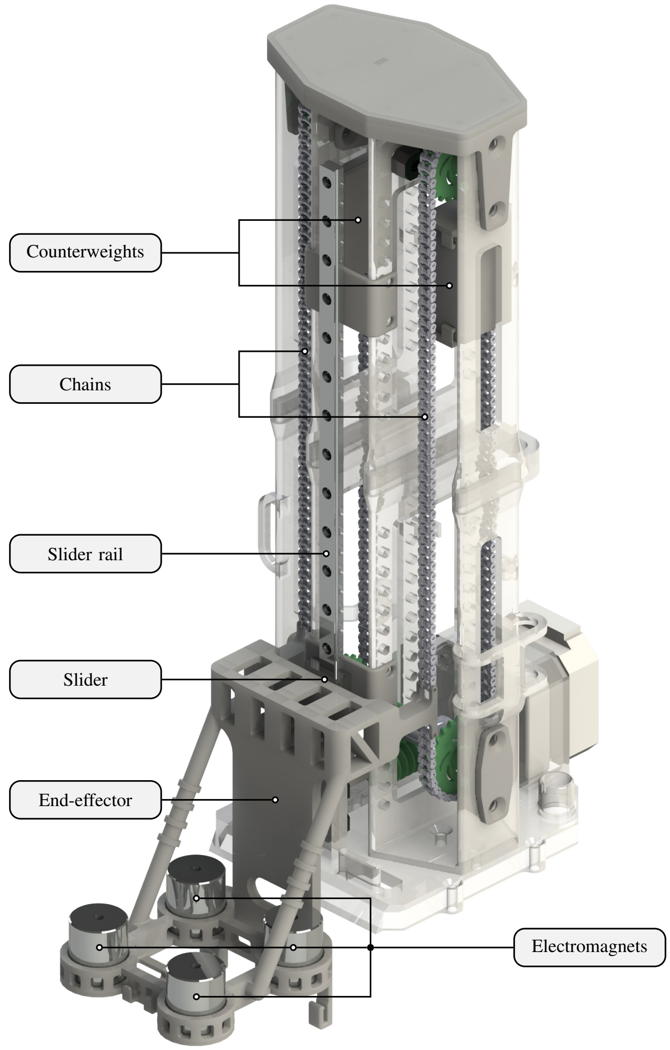


Fig. 5. Component diagram for the manipulator.

COM provides two camera serial interface (CSI) ports, which enable the simultaneous capture of video from two sources. These CSI ports connect to dedicated image processing hardware, which supports resizing, compression, and direct memory access (DMA). We have designed a camera circuit board for the autonomous robot, which provides an interface between a 5MP OmniVision image sensor and a CSI port on the microprocessor circuit board.

The microprocessor circuit board also provides an SD card slot for capturing data from experiments, a USB host port for connecting peripherals, a connector for an XBee wireless module, and a USB peripheral port for debugging. The USB peripheral port connects to an on-board USB hub, which enables low-level access to the microprocessor's console, using a USB-to-serial converter, and high-level access to the operating system, using a USB On-The-Go (OTG) Ethernet connection. The on-board hub is compliant with the USB battery charging specification and provides power to the robot for recharging its batteries.

The specialized manipulator also consists of two circuit boards: the manipulator circuit board and the interface circuit board. The manipulator circuit board monitors and controls a stepper motor, which regulates the height of an end-effector. The manipulator circuit board also provides the pre-charging circuitry for four semi-permanent electromagnets in the end-effector (Fig. 4). This circuitry can strengthen or weaken the magnetic field of the electromagnets, causing a stigmergic block to attach to or detach from the end-effector respectively.

The interface circuit board is attached to the end-effector and is equipped with two range finders and an NFC interface for communicating with a stigmergic block. In addition, two range finders (one on the front of the end-effector, and one hidden underneath) and a camera circuit board, which is tilted 45 degrees towards the ground, are attached directly to the end-effector. When the end-effector is at its maximum height (3.5 blocks, or 192.5 millimeters), the autonomous robot can detect blocks on the ground up to approximately 350 millimeters away from its center. At the end-effector's minimum height (1 block, or 55 millimeters), the robot can track a block until it disappears underneath the end-effector. At this point, the robot uses the range finders on the end-effector to make final adjustments to its position and orientation before picking up a block.

B. Mechanical Design

Fig. 5 shows the mechanical design of the manipulator, which consists of off-the-shelf components and parts printed

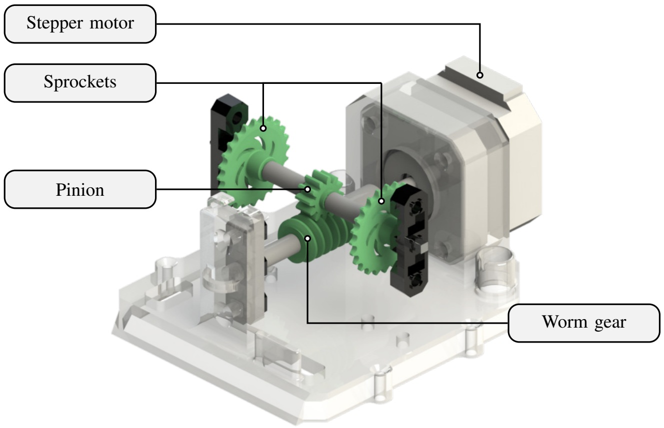


Fig. 6. Component diagram for the base of the manipulator.

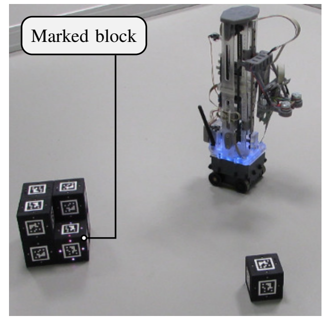
using stereolithography. The overall height of an autonomous robot is 370 millimeters. Fig. 6 shows how the stepper motor is mechanically coupled with two sprockets. These sprockets rotate to raise and lower two chains to which the end-effector is attached. A slider rail limits the motion of the end-effector so that it only moves vertically. The weight of an end-effector is offset using lead counterweights.

C. Software

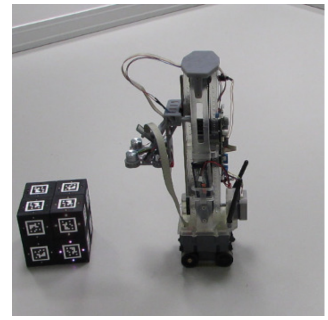
The low-level software of an autonomous robot is distributed over three microcontrollers, one on the manipulator circuit board and two on the power circuit board. These microcontrollers control the hardware on each circuit board and communicate with the microprocessor over UART using a custom protocol, which provides framing and checksumming.

The microprocessor runs a custom distribution of Linux, which we have built from scratch using the Yocto Project. The sensors and actuators of an autonomous robot are made available to the high-level software using loadable kernel modules. The behavior of a robot is currently implemented as a single binary executable.

This executable initializes an autonomous robot before starting its control loop. The control loop samples the robot's sensors, updates its actuators, and advances its state machine. The robot's computer vision is implemented as a partially-asynchronous image processing pipeline. The asynchronous component of this pipeline captures images from the camera, runs the stigmergic block detection algorithm, and can optionally save the processed images to local storage or stream them to a remote PC. The synchronous component of this pipeline implements the block tracking algorithm and structure detection. The block tracking algorithm is based on the Hungarian algorithm and uses a modified cost matrix to accommodate new and lost targets [22]. Under good lighting conditions, the update rate for the control loop is approximately 150 milliseconds. To ensure a constant update rate for the high-level control loops, however, a delay is added to force the update rate to 200 milliseconds.

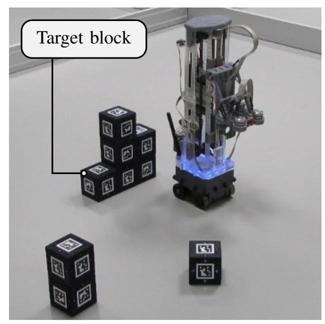


(a) Initial setup.

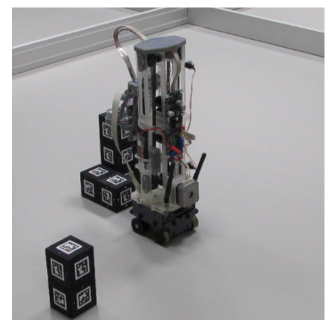


(b) Task complete.

Fig. 7. Markings-based task.



(a) Initial setup.



(b) Task complete.

Fig. 8. Structure-based task.

The control loop runs until the finite state machine exits or an interrupt signal is received. Once the control loop exits, the executable sends commands to the remote microcontrollers to shut down the differential drive and stepper motor controllers. At this point, the executable exits to the Linux shell.

VI. Verification

To verify our decentralized control strategy and autonomous construction system, we have the robot perform three different tasks with stigmergic blocks. These tasks demonstrate how both structure-based and markings-based stimuli, facilitated by the blocks in a partially-built structure, may be used to coordinate construction.

The first task is designed to verify that the autonomous robot can respond to a markings-based stimulus (Fig. 7). In this task, the robot must locate and pick up an unused block and place it on top of an illuminated block that forms part of a structure. The robot performs this task as follows: (i) the robot turns on the spot, searching its environment for an unused block, (ii) upon locating an unused block, the robot approaches it and picks it up, (iii) the robot continues to turn on the spot, searching for an illuminated block that forms part

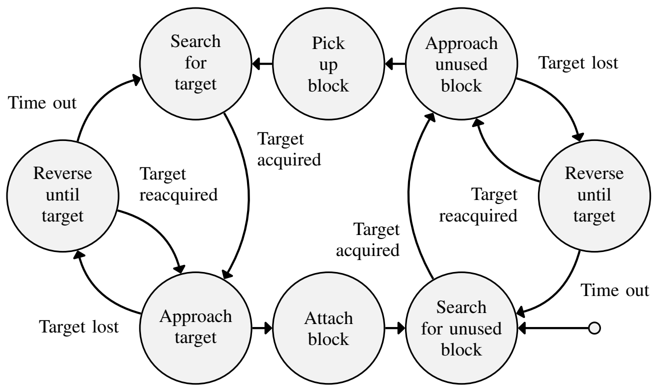


Fig. 9. Behavioral state machine for an autonomous robot.

of a structure, (iv) upon locating an illuminated block that forms part of a structure, the robot approaches the illuminated block and places the unused block on top of it.

In the second task (Fig. 8), we verify that the autonomous robot can respond to a structure-based stimulus. The task requires the robot to locate and pick up an unused block and place it against the larger of two detected structures. The size of a structure is estimated using a heuristic: If a block in a structure has more adjacent blocks than the currently selected block, the robot selects the block with the highest number of adjacent blocks; otherwise, the robot uses the number of adjacent blocks of the currently selected block as an estimate of the structure size. The robot performs this task as follows: (i) the robot turns on the spot, searching its environment for an unused block, (ii) upon locating an unused block, the robot approaches it and picks it up, (iii) the robot continues to turn on the spot, searching for a structure, (iv) upon locating a structure, the robot estimates its size and continues searching its environment for a second structure, (v) upon locating the second structure, the robot estimates its size, (vi) if the first structure was larger, the robot turns on the spot in the opposite direction until it locates the larger structure again (vii) the robot places the unused block against the leftmost block in the larger structure.

In the third task, we demonstrate how a combination of both structure-based and markings-based stimuli can be used to coordinate construction. This task requires an autonomous robot to assemble a staircase from six stigmergic blocks. An environment is set up with two blocks: a seed block illuminated in the Q3 color (green) and an unused block. At the start of the demonstration, a robot is placed between the two blocks. The state machine in Fig. 9 shows the behavior of the robot as it cycles between locating and picking up unused blocks and attaching them to the partially-built staircase. Alg. 1 describes how the robot responds to the structure-based and markings-based stimuli of the partially-built structure.

```
set target_block to highest block in frontmost_column;
switch target_block.type do
    case Q3 do
        if target_block.height < 3 then
            set unused_block.type to Q3;
            stack unused_block on target_block;
        else
            set unused_block.type to Q2;
            extend frontmost_column with unused_block;
        end
    end
    case Q2 do
        if target_block.height < 2 then
            set unused_block.type to Q2;
            stack unused_block on target_block;
        else
            set unused_block.type to Q1;
            extend frontmost_column with unused_block;
        end
    end
    case Q1 do
        shut down;
    end
end
```

Alg. 1. Algorithmic description of the *attach block* state from the behavioral state chart in Fig. 9.

By configuring the color of a stigmergic block prior to attaching it to the structure, the autonomous robot modifies the partially-built staircase, so that the resulting stimuli from the blocks in the structure coordinate further construction.

Fig. 10 shows the various stages of the autonomous robot constructing a staircase from the stigmergic blocks. A video of this demonstration is included in the supplementary material for this paper. Due to uneven friction and occasional jamming of the drive system, we have assembled this demonstration from multiple runs. We are currently working on resolving this minor issue with our hardware.

VII. Conclusion

We have presented a decentralized control strategy that uses the structural arrangement of blocks in a partially-built structure and their markings as stimuli to coordinate construction. In this control strategy, coordinated construction occurs as a result of a feedback loop where construction modifies a partially-built structure, and where the modifications to a partially-built structure may be used to coordinate further construction. To demonstrate this control strategy, we have designed an autonomous construction system consisting of an autonomous robot and stigmergic blocks. We have used this construction system to perform three tasks, including the construction of a staircase.

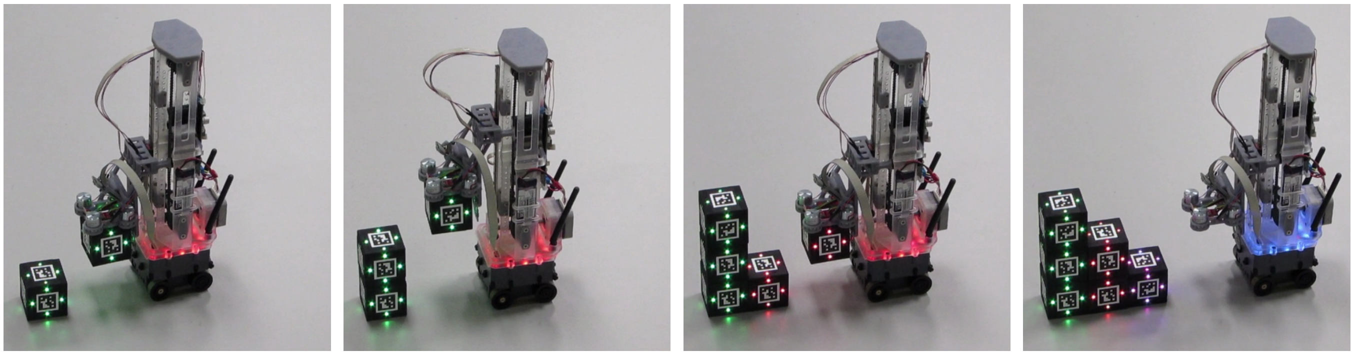


Fig. 10. Construction of a staircase by an autonomous robot, coordinated through the structure and markings of the partially-built structure.

This paper represents a milestone in our research towards the implementation of a swarm robotics construction system, which is inspired by the construction capabilities of social insects in nature. To this end, we intend to generalize our decentralized control strategy to enable the construction of a variety of structures in various settings with multiple robots.

ACKNOWLEDGMENTS

Marco Dorigo acknowledges support from the Belgian F.R.S.-FNRS, of which he is a Research Director, and from the FLAG-ERA project Robocomm++. Navneet Bhalla was partially supported by a postdoctoral fellowship from the Natural Sciences and Engineering Research Council (NSERC) of Canada. We thank Haitham El-faham for his help with the first prototypes of the manipulator and Anthony Antoun for his help with the first prototype of the stigmergic block.

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