Emergent Structures Assembled by Large Swarms of Simple Robots

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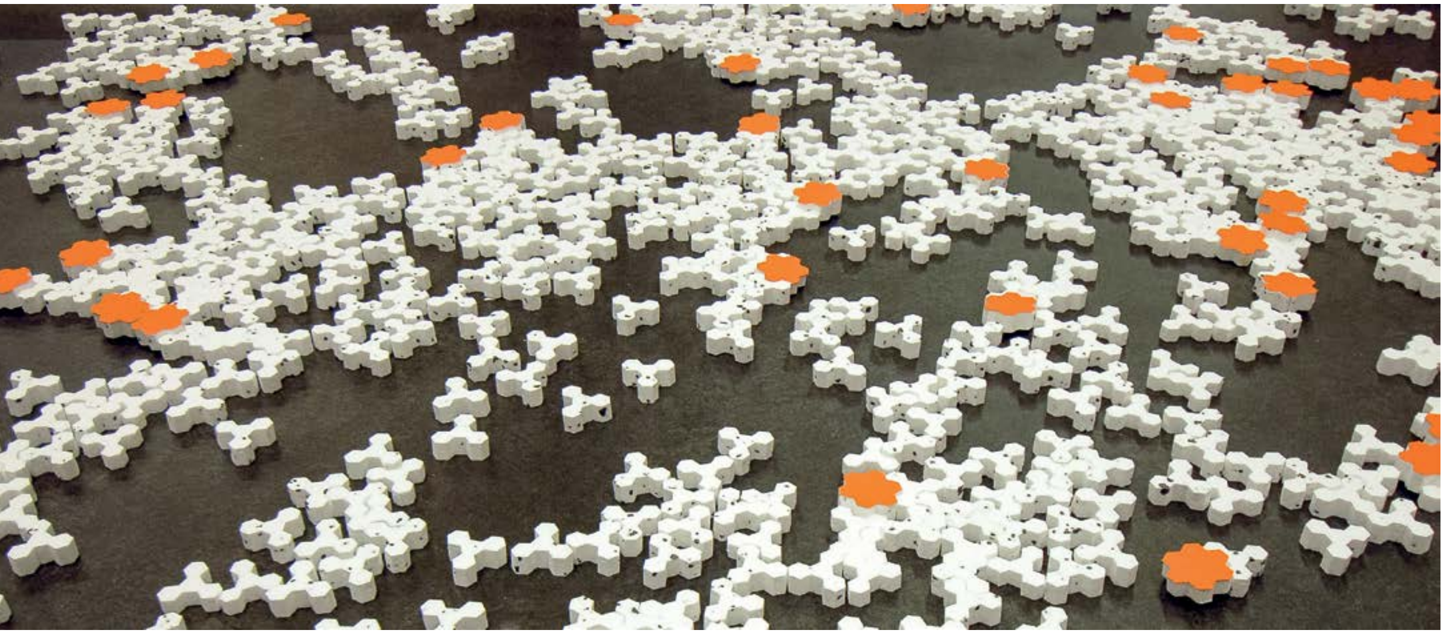


1 View of testbed with robots (orange) and passive blocks (white) at the SmartGeometry conference in Göteborg 2016.

ABSTRACT

Traditional architecture relies on construction processes that require careful planning and strictly defined outcomes at every stage; yet in nature, millions of relatively simple social insects collectively build large complex nests without any global coordination or blueprint. Here, we present a testbed designed to explore how emergent structures can be assembled using swarms of active robots manipulating passive building blocks in two dimensions. The robot swarm is based on the toy "bristlebot"; a simple vibrating motor mounted on top of bristles to propel the body forward. Since shape largely determines the details of physical interactions, the robot behavior is altered by carefully designing its geometry instead of uploading a digital program. Through this mechanical programming, we plan to investigate how to tune emergent structural properties such as the size and temporal stability of assemblies. Alongside a physical testbed with 200 robots, this work involves comprehensive simulation and analysis tools. This simple, reliable platform will help provide better insight on how to coordinate large swarms of robots to construct functional structures.

INTRODUCTION

Driven by new technologies and increasingly complex and challenging construction environments, the field of multi-robot systems with distributed control is gathering interest. The allure lies in the potential for rapid, in-situ construction, continuously responsive and evolving buildings, and the colonization of human-hostile environments such as areas of disaster, the deep sea, or space.

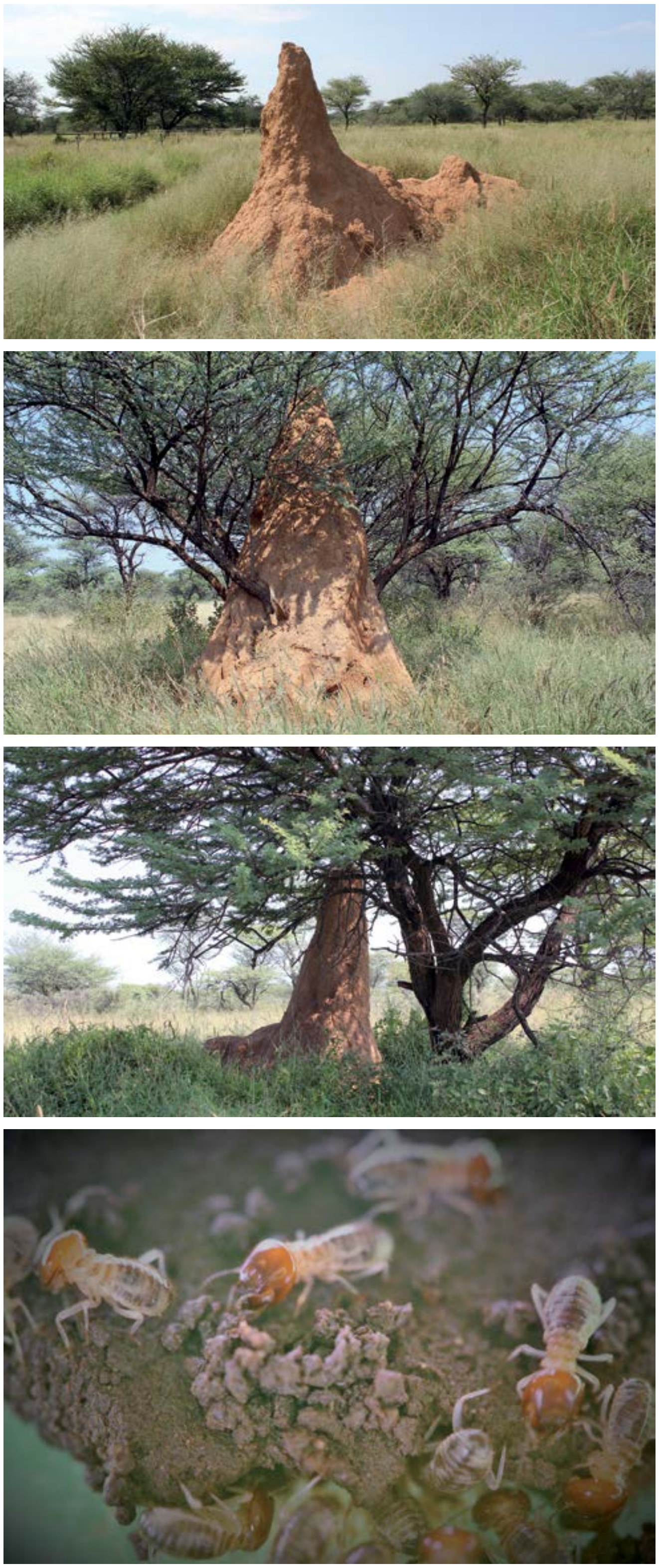
In such situations, swarms—coordinated groups of autonomous agents—exhibit a number of advantageous traits: *Redundancy*, where robustness to failure is achieved through the sheer number of agents; *parallelism*, where many agents can work efficiently on the same structure at once; *scalability*, where additional agents can be added to perform a larger task or complete one more rapidly; and a*daptability*, where the system has the potential to respond to external disturbances. In other words, swarms of robots are potentially robust, responsive, and adaptable constructors, lacking many of the limitations found in automated centralized processes.

However, building, maintaining, and coordinating large robot swarms is a challenging problem, especially as the complexity of individual robots increases. Furthermore, achieving predictable complex emergent outcomes from bottom-up programming is difficult. Instead, it may be beneficial to find simpler methods for collaborative organization, such as the mechanical programming explored here. Minimally complex agents physically interact, and outcomes are controlled by carefully designing the geometry of the agents and their environment.

In pursuit of this goal, we have set up a testbed and organized a workshop to explore emergent self-organizing behavior of a large number of simple robots. The testbed is composed of a physical arena which includes active robots (bristlebots) and passive building blocks, a digital simulation of the physical testbed, and a kit of analysis tools which allow for a performative evaluation of the emerging structures and behaviors. In the future, we hope to use this testbed to understand and formalize methods of achieving emergent structures with predictable properties, based solely on manipulation of the geometry of the robots and building blocks.

Inspiration

Architects have long been intrigued by the emergent properties of swarms. Miranda and Coates (2000) outline some of the system characteristics, albeit in a virtual environment, highlighting the combination of simple mechanics and complex emergent phenomena. Tibbits (2012) takes the investigation a step further by moving to physical contexts and omitting programmed control, instead relying on geometric properties and



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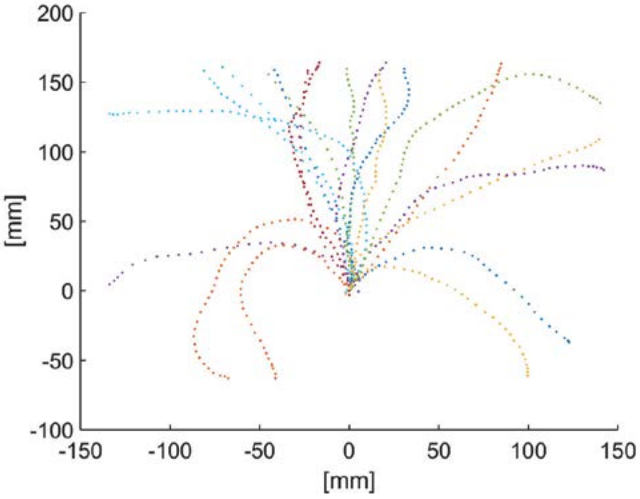
2 No two termite mounds look the same; the structure emerges from the local interactions between millions of relatively simple insects always resulting in a unique, but functional, output.



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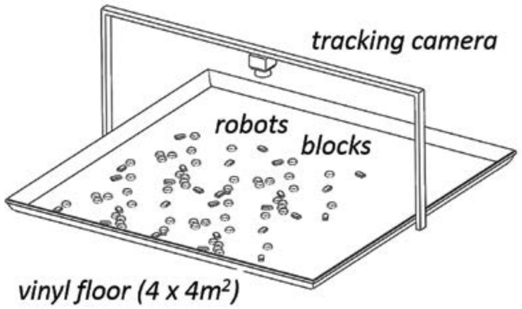

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3 Tracked paths of 20 bristlebots started from (0,0) heading along the vertical axes; although most move somewhat straight, some are predispositioned to circular motion patterns.

4 Photos showing the original bristlebot, bristlebot with Styrofoam cover, and final bristlebot with a colored cardboard top for tracking purposes.

5 Sketch of testbed area.

mechanical coding to achieve predetermined outcomes.

Leaving the field of architecture, the natural and biological precedent is strong and forms the clearest inspiration for the work documented here. Self-organization is found in many places in nature, often as a performative survival strategy. One example, as outlined by Ben-Jacob (2010), is in single cell bacteria, where the brainless organisms form complex spatio-temporal patterns. Another example is the construction of functional nests and mounds by termite colonies without any centralized coordination or sensing (Turner and Soar 2008; Figure 2). The termites have served as a model for previous efforts to design collective construction robots (Werfel, Petersen, and Nagpal 2014; Napp and Nagpal 2014), but these systems quickly escalate in design complexity due to the requirements of executing specific bio-inspired algorithms.

In general, large collectives of robots are rarely presented, because of implications regarding maintenance, cost, and reliability. The single largest swarm presented was 1,024 robots (Rubenstein, Cornejo, and Nagpal 2014). Using distributed control and local communication, these robots could aggregate to form loosely connected 2D shapes. In contrast to the hardware platform presented in that research, we use inexpensive commercially available robots, which are very robust and able to move over a much larger variety of surfaces. In the analysis section, we show how system properties such as temporal stability, structural stability, and propensity to form clusters are greatly affected by geometry and can be tuned by changing the degree and type of mechanical interlocking. Through this project, we seek to explore how more fundamental mechanisms of emergent form can be found and navigated; this may later serve as a foundation for more complex templates.

METHODOLOGY

Robot Testbed

The robot testbed is based on a large two-dimensional arena containing passive building blocks and up to 200 bristlebots. Input variables such as the geometric shape and number of robots and blocks, initial configuration, and permanently mounted mechanical shapes determine the properties of the output structure. A camera (Logitech C920) mounted overhead records the experiments for subsequent analysis.

The robots are commercially available (Hexbug Nano ver. 1), propelled forward by a simple vibrating motor on top of angled soft legs, and have no means of programming other than changes to their body geometry. They all exhibit some degree of randomness in their movement; furthermore, some robots tend to move fairly straight, while others have a circular motion pattern of different radii (see Figure 3). By bending the legs, these patterns can be altered. The robots operate on an AG13 battery, with a battery life of approximately 45 minutes, holding an average speed of approximately 11 mm/s.

The robot shape is altered by adding a customizable cover (Figure 4). Although the movement pattern of the robot is not strongly influenced by the covers tested here, covers that are too large or front heavy will severely alter the movement/decrease the velocity of the robot.

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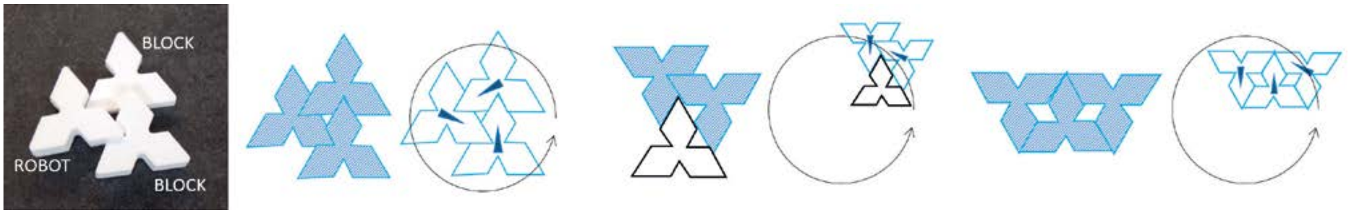

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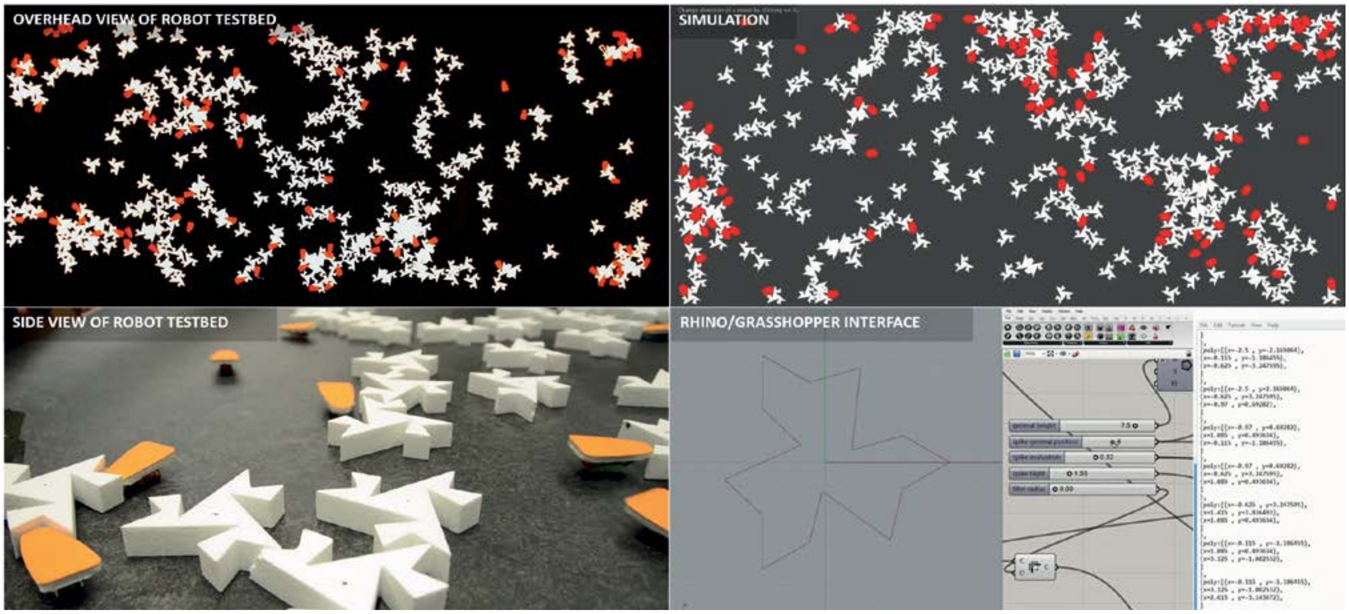

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6 Photo sequence of small-scale experiment: the geometric shape of the robots prompts them to form emergent chains for collective transport of heavy objects.

7 Spatio-temporal patterns formed using passive and active triangular shapes, depicted with motion patterns in decreasing order of stability.

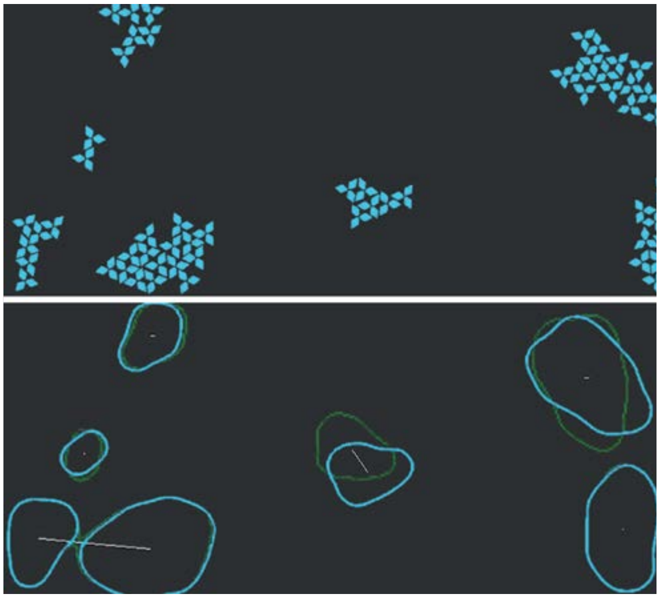
8 Upper left: frame from the recorded video where each pixel is classified as background, building block, or robot, and colored accordingly. Upper right: snapshot of the simulation. Lower left: close-up photo of the robots and building blocks. Lower right: Rhinoceros 3D/Grasshopper interface allows users to quickly modify and test new geometric shapes in both simulation and real life.

The robots operate in an arena of variable size, up to 4 x 4 m^2, covered with a dark vinyl rug. Because the robots tend to get stuck along vertical walls, the edges of the vinyl are bent up to form a soft boundary that provides a passive incentive for the robots to turn back into the arena (Figure 5).

In addition to the bristlebots, passive building blocks of CNC-cut styrofoam are placed in the arena. The tracking of these blocks is the primary mode to evaluate the outcome of the experiment, along with behavioral analysis of the robots. The photo sequence in Figure 6 gives an example of the type of complex outcome one can achieve despite the simplicity of the system. By matching the robot gripper to the robot rear they can form long emergent chains that can move objects too heavy for a single robot. Figure 7 shows a system where the same shape is used for robots and building blocks, providing interesting metastable and stable shapes for spatio-temporal outputs.

Simulation

A simulation environment was implemented with Processing (Reas and Fry 2006) using Box2D (Catto 2011) as a physics



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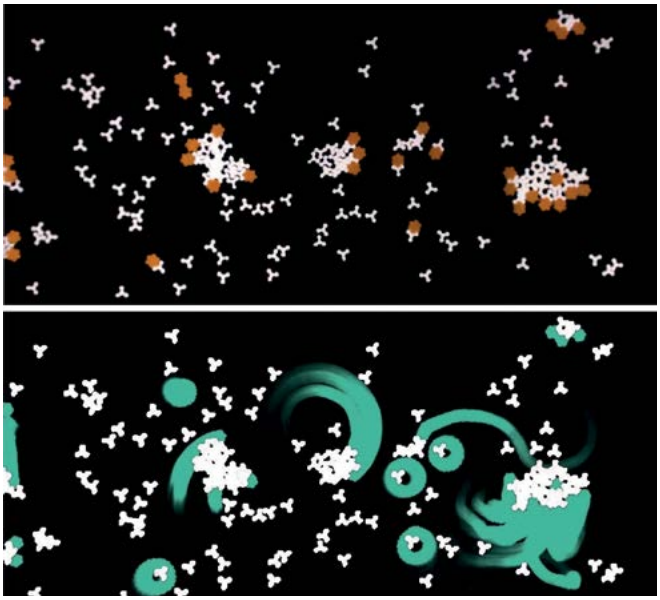

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9 Experiment with triangular shaped robots (from Figure 4) without passive building blocks. The figure shows a screenshot from the digital simulation and an analysis of the cluster sizes and migration between two timestamps.

10 Top: Still image from video recording of experiment. Building blocks are white, and robots orange. Bottom: Analysis of video, robots with fading trails are shown in green. Single robots pushing only one block tend to get stuck in a circular pattern of a set size, while the bigger clusters are moved by the collective effort of several robots.

engine; it consists of a 2D world with both active agents and passive building blocks. This simulation tool complements the robot testbed by enabling fast iterations of geometric design, easy replication of experiments, and the ability to explore the population scale at which the rules, which are hard-coded into the robots, no longer produce meaningful structural properties.

All simulated objects have ground friction (modeled as velocity damping), object-object friction, density, and a coefficient of restitution; their shape is defined by one or more convex polygons and circles. The agents differ from the passive blocks by an applied force vector along with a certain degree of noise to create movement patterns which match the physical robots. The object parameters were adjusted to achieve behavior similar to that observed in the physical experiments. To mimic the soft boundaries of the physical arena, a repellent force has been added to the world boundaries. As the simulation runs, it automatically produces video output and log files for subsequent analysis.

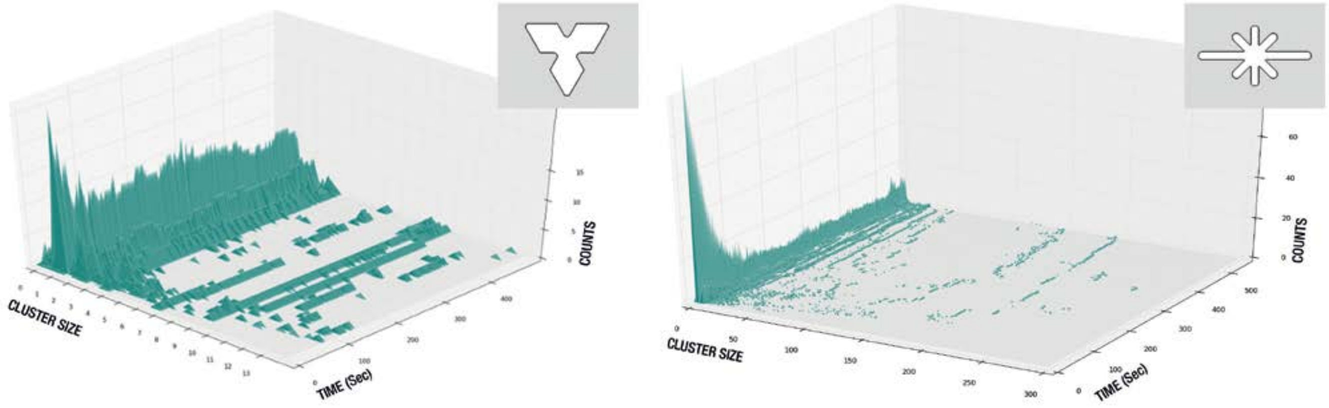
Finally, a small script was added in Grasshopper (www.grasshopper3d.com) and Rhinoceros 3D (www.rhino3d.com) to enable quick iterations of geometric shapes, simulation, and production of physical blocks and robots (Figure 8).

Analysis

A set of analysis tools has been developed to aid in understanding the emergent behavior arising from the mechanical program, as well as understanding the similarities between the physical experiments and the digital simulations. They look at both the passive building blocks and the robots themselves. The primary focus is on visualizing the assembly process by analyzing the evolution of building block clusters and their robot induced motion.

The video data is analyzed using the Python interface to the computer vision library OpenCV (Bradski 2000). Through the use of color information, the video is segmented into background, passive building blocks, and robots, and can be passed on for further analysis. In the case shown in Figure 9, the assemblies are analyzed using Grasshopper 3D for the number and size of discrete clusters over time by counting the number of parts associated with each cluster.

The ability to process robots and passive building blocks separately also makes it possible to visualize robot motion; in Figure 10, for instance, the location of the robots is plotted over time. This analysis can be done both on recorded videos of the physical experiments as well as the digital simulations to visualize how collective motion patterns emerge when several robots form clusters linked via passive blocks. This collective transport behavior emerges even though there is no central control, and the robots are programmed using mechanical shape only. A single robot can push a maximum of approximately 3 building blocks, depending on size and shape of the blocks, while larger clusters of blocks can be pushed when several robots work together.



11 Cluster sizes of building blocks plotted over time. Peak shows initial state where blocks are randomly dispersed, after a while stable clusters form indicated by "lines" along the time axis. Different physical shapes lead to fundamentally different behaviors. The plot to the left shows clusters of triangular robots, which can quickly form stable small clusters (Figure 4), while the plot to the right shows clusters of star-shaped blocks, which tend to aggregate into larger stable clusters too large to move.

Similarly, the assembly process can be observed by plotting cluster properties over time. Figure 11, for instance, shows how semi-stable clusters of passive blocks form over time depending on their geometry.

Observations

The intention of this article is primarily to describe an experimental set-up, rather than to establish definitive links between the agents' geometry and the large scale patterns that emerge, which is left for forthcoming research. However, some observations were made during the course of the workshop that may serve as initial guidelines or hypotheses for such research. These observations are somewhat intuitive and qualitative in nature and would require further confirmation from quantitative data.

1. *Density*. The overall density of blocks and robots greatly affect the outcome. When the robots or blocks are sparse, random movements tend to dominate, and the blocks and robots aggregate along the outer perimeter of the testbed. Conversely, with too many blocks or robots, the system locks up due to congestion and little change over time is observed.

2. *Cluster stability*. In order to form stable clusters that do not disperse over time, the robots and/or blocks must be able to interlock with one another. Figure 4 shows an example where the blocks aggregate to form stable clusters over time, and Figure 3 shows how robots can interlock to make them move in conjunction with each other.

3. *Directed motion*. Blocks may counteract the random movement of a robot through negative feedback. An example is the triangular blocks shown in Figure 4; a passive block in front of a robot will dampen the random movements of the robot, making it move mostly straight.

4. *Collective transport*. Combined, interlocking features and the ability of blocks to alter motion patterns of the robots lead to interesting swarm behaviors, such as robots jointly moving large clusters of blocks along straight paths, as shown in Figure 7. In Figure 3, robots sporadically interlock and are thereby able to push objects that would be too heavy for an individual robot.

CONCLUSION

In this article we explore 2D construction processes with emergent outcomes by using swarms of robots and passive building blocks; the swarm behavior is programmed by changing the geometric shape of both robots and blocks. We develop and present the necessary tools for designing and analyzing such systems, including a physical robot testbed and a detailed simulation environment. The behavior of each individual robot is simple, but the shape-mediated interactions with other robots and passive blocks can lead to complex swarming patterns, for example, forming stable clusters of specific size or collective transport.

By focusing on a simplified 2D environment with commercially available, cheap, and robust robots, we can physically implement the swarm on a scale much larger (200 robots) than is commonly seen in literature. Having full control over all input parameters, including population size and geometric shape, as well as the world perimeter, allows efficient exploration of which parameters have the greatest effect on structure outcome.

The physical testbed is complemented by a customized simulation platform and design tools allowing more rapid iterations and automated tests of new shapes than is possible in real life, which is essential due to the complexity of agent interaction.

The presented analysis tools are general and scale well with respect to swarm size. By working directly on video data, we can use the same analysis toolchain on both simulated and real-world data, and establish that the two systems behave similarly. Here, we have focused on evaluating the evolution of cluster sizes, but more specialized measures are possible. For example, cluster shapes and locations could be influenced by designing building blocks that induce preferential growth directions or initiate cluster formation based on arena geometry.

Looking forward, we aim to use this testbed to improve our understanding and develop formalized theories of how to adapt local rules (geometry) according to desired global outcomes. Other extensions of this work might focus on closing the loop in the design process by optimizing shapes for specific properties, either through stochastic optimization schemes like genetic algorithms (Davis 1991) or recent work on Bayesian optimization that aims to efficiently use simulations to form priors on measurements in physical experiments. These methods have been successfully used for optimizing large design spaces, and coupling our design and analysis tools to run these algorithms might enable us to find shapes that produce strong and reliable emergent behavior in a bottom-up fashion.

The advantages of the simple robot swarms presented here—their robustness, adaptability, and scalability—can provide significant benefits in real world construction scenarios. By providing this framework where questions of control and predictability of the emergent structures can be explored and tested, we hope to contribute to the field of construction by robot swarms.

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IMAGE CREDITS

Figure 8: Lochnicki, Hwang, and Nygren, 2016
Figures 9–10: Cihocka, Larsen, and Soorati, 2016
All other figures: Andréen, Jenning, Napp, and Petersen, 2016

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Petra Jenning (SAR/MSA) recieved her MArch from Lund University in Sweden in 2007. She has since practiced architecure in Shanghai, Paris, London and Malmö. She has taught at University of Greenwich, been an invited critic at the AA, CITA, and LTH, and run workshops in several universities and companies. Currently she is head of computational design at FOJAB architects in Sweden.

Nils Napp received his Bachelor of Science in Engineering and Mathematics from Harvey Mudd College, Claremont CA, in 2003 and his MS and PhD in Electrical Engineering from the University of Washington, Seattle WA, in 2006 and 2011 respectively. Before joining the University at Buffalo, Buffalo NY, as an Assistant Professor of Computer Science and Engineering in 2014 he was a post-doctoral fellow at the Wyss institute for Biologically Inspired engineering at Harvard University, Cambridge MA. His research focuses on robotics and biologically inspired algorithm design that enables engineered systems to robustly interact with their environment.

Kirstin Petersen received a BSc in electro-technical engineering from the University of Southern Denmark, and a PhD in Computer Science from Harvard University in 2014. Her thesis involved design of autonomous robots for collective construction inspired by African mound-building termites. She did a 2-year postdoc on novel soft actuator mechanisms at the Max Planck Institute for Intelligent Systems in Germany, and is currently an assistant professor in the ECE department at Cornell University, USA. Her research interests involve bio-inspired robot collectives able to interact with and manipulate their environment according to user-specified goals.