Eciton robotica: Design and Algorithms for an Adaptive Self-Assembling Soft Robot Collective

Melinda Malley[1], Bahar Haghighat[1], Lucie Houel[2] and Radhika Nagpal[1]

***Abstract*— Social insects successfully create bridges, rafts, nests and other structures out of their own bodies and do so with no centralized control system, simply by following local rules. For example, while traversing rough terrain, army ants (genus *Eciton*) build bridges which grow and dissolve in response to local traffic. Because these self-assembled structures incorporate smart, flexible materials (i.e. ant bodies) and emerge from local behavior, the bridges are adaptive and dynamic. With the goal of realizing robotic collectives with similar features, we designed a hardware system, *Eciton robotica*, consisting of flexible robots that can climb over each other to assemble compliant structures and communicate locally using vibration. In simulation, we demonstrate self-assembly of structures: using only local rules and information, robots build and dissolve bridges in response to local traffic and varying terrain. Unlike previous self-assembling robotic systems that focused on lattice-based structures and predetermined shapes, our system takes a new approach where soft robots attach to create amorphous structures whose final self-assembled shape can adapt to the needs of the group.**

I. INTRODUCTION

Imagine a swarm of robots transporting heavy cargo and encountering a steep ledge or cliff: Instead of getting stuck, they form a ramp, and traverse the obstacle. After the task is completed, the robots dissolve the bridge and continue on their way. Nature has already achieved this: many social insects self-assemble into bridges, rafts, pulling chains, even entire nests with no centralized control, only local rules [1].

Self-assembled structures enable insects to behave more efficiently and perform activities that are beyond the capacity of individuals. Army ants (genus *Eciton*) are a particularly impressive example – ants are able to form bridges, chains, and even their nests (called bivouacs) from their own bodies to support their nomadic lifestyle. While collecting prey, army ants self-assemble bridges which create short-cuts across rough terrain, allowing them to move quickly and efficiently. Unlike most structures built by humans with conventional construction methods, these bridges are amazingly adaptive and dynamic. Biologists have shown that army ants bridges not only conform to the geometry of the terrain, but also dynamically respond to the level of traffic [2], [3], [4]. At high traffic flows, larger bridges form; if traffic stops altogether, the ants in the bridge disassemble and return to other activities. This type of self-assembly allows insects to flexibly solve temporary problems and deal with emergency situations in their environment [1].

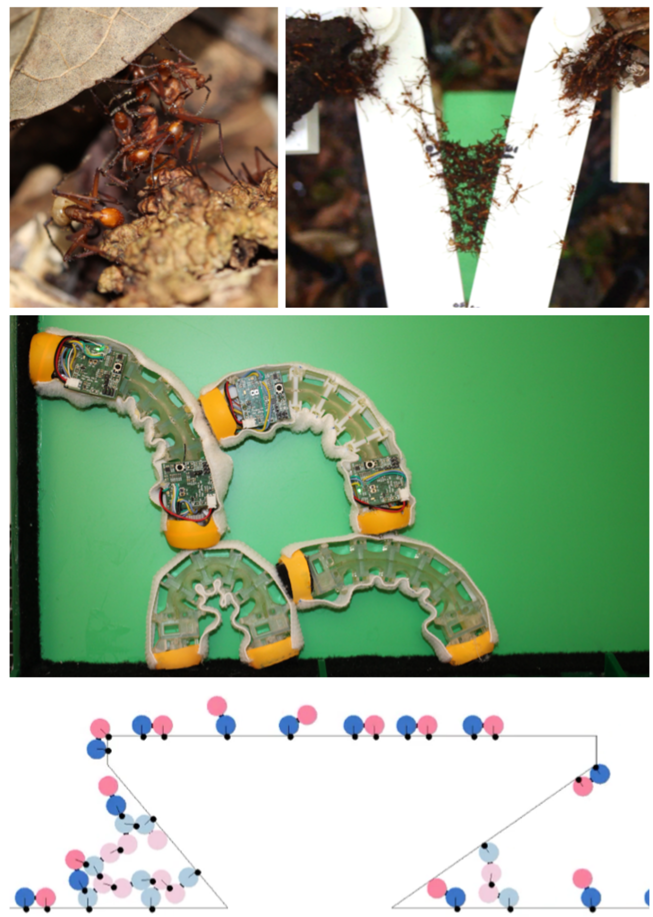

Fig. 1: **Top**: A natural bridge formed by *Eciton hamatum* (Left) and an experimental set-up with the same species (Right, image courtesy of Reid, Lutz, Garnier [4]). **Center**: *Eciton robotica* in a potential ramp structure with two active robots. **Bottom**: Simulated robots form a structure that smooths traffic over rough terrain. Light colors indicate that the agents have gone into a "bridge" state and are stationary.

In this paper, we present the design of a novel self-assembling robot collective, *Eciton robotica*, inspired by adaptive bridge formation of army ants. Most previous work in self-assembling robotic systems has focused on rigid robots that form predetermined lattice-based shapes. These structures are predictable and efficient but lack the ability to conform to a new environment or adapt to different

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[1]School of Engineering and Applied Sciences at Harvard University, Wyss Institute for Biologically Inspired Engineering melindamalley@fas.harvard.edu

[2]École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

conditions without outside intervention. To the best of our knowledge, *E. robotica* is the first self-assembling or modular robot system to use soft, flexible individuals designed to create structures which conform and adapt to different environments.

The hardware system consists of flexible climbing robots shown in Fig. 1, Center, that can climb over any velcro surface, using a biped flipping motion and grippers on either end. Velcro covers the length of the robot body, allowing them to climb over each other just as they would any other velcro surface, with simple local sensing and control. They sense the presence of other robots climbing over them using a vibration communication system inspired by natural systems [5]. The current implementation consists of two fully autonomous, untethered robots and two passive modules.

To self-assemble ant-like adaptable structures, the robots use a simple bio-inspired local control rule. While army ant bridges respond to local traffic [3], the rules individual ants use to do this are not well understood. One simple hypothesis is that ants simply stop and become part of structure when they are stepped on by other ants - responding to congestion by creating a structure that alleviates it [2], [3]. To test this idea, we created a simple model of our robot system in simulation using the Box2D physics simulator. We ran experiments over a variety of traffic levels, using a V-shaped terrain inspired by the army ant experiments by [4], shown in Fig. 1. Our experiments show that, with this rule, the robot system can self-assemble structures which respond to the local traffic and terrain and dissolve when they are no longer needed.

II. RELATED WORK

Previous work on self assembling robotic systems, including modular and reconfigurable robots, has largely focused on the creation of predetermined, lattice-based structures [6] where robot modules latch onto one another at fixed docking sites. A blueprint of the desired target structure is encoded in the form of a map or a set of rules and programmed on the robotic modules, guiding the assembly process. Most systems are based on cubic lattices or chain-style configurations [6], e.g. [7], [8], [9], [10], [11]. A subset of these systems can act as robot swarms where each robot is autonomous and mobile on its own, but can also self-assemble with other robots [12], [10], [13], [14]. Two advanced systems that can self-assemble structures in 3D are SMORES [12] and M-Blocks [10], where independently mobile robots reconfigure by pivoting around other robots.

The above robotic systems use rigid agents with fixed docks to create user-defined lattice shapes, with the goal of self-assembling precise and reliable structures. In contrast, army ants have flexible bodies and can attach to each other at any point. Their self-assembled structures are soft and compliant; they can conform to many environments and dynamically adapt to the changing needs of the colony. Few examples of this sort of adaptive or dynamic self-assembly exist in robotics: Swarmbots [9] have been used to create adaptive pulling chain structures, and Slimebots [15] adaptively reconfigure for locomotion on a flat surface. While closer to ants, these systems use robots made completely from rigid parts. Taking inspiration from army ants, where soft-bodied individuals create non-lattice structures, the *Eciton robotica* system uses a flexible soft-bodied robotic module which is designed to follow simple local rules to form bridge structures that adapt to the environment and traffic conditions.

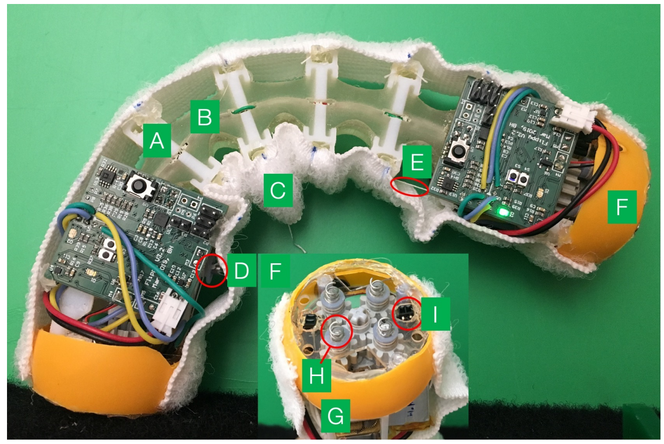


Fig. 2: An *Eciton robotica* agent. The body is composed of rigid (A) and flexible (B) portions, and is covered in stretchy Velcro loop (C). A motor and spool (D) winds a cable (E) on both the top and bottom to control the bending of the robot. Grippers (F) on each end attach to velcro surfaces. A motor (G) on each gripper controls the four corkscrews (H) to attach which wind into the velcro. Two IR sensors (I) detect when a gripper has made contact with a new surface.

III. ROBOT HARDWARE SYSTEM

For a self assembling robot swarm to build ant-like adaptable structures, individual robot agents need to be autonomous, untethered, able to climb over complex terrain and other agents, and able connect to each other at any point along their bodies. The *E, robotica* system accomplishes this with flexible, flipping bipeds, which use corkscrew grippers on each end to attach to and climb over Velcro loop surfaces. Since the robots are covered in Velcro, they climb over each other just as they do other surfaces. The current implementation consists of two fully autonomous agents that can self-assemble in 2D, and two inactive modules for testing purposes (Fig. 1). The robots are able to move freely, but lack steering; thus experiments are performed in a planar box which constrains the path of the robot to two dimensions.

Mechanical Design: The *E. robotica* robot is shown in Fig. 2; it is an adaption of a previous autonomous climber, Flippy [16] which alternates gripping and flipping to move forward and climb. The body is composed of alternating 3D printed rigid and flexible segments. Two DC motors on either side of the robot wind and unwind spools of cable to control the bending of the robot and execute the flipping gait. Each cable is connected to a mechanical switch which senses tension in the cable and prevents tangling.

Fig. 3: An *E. robotica* robot climbs over a second robot, which detects its presence as indicated with pink LEDs.

As with the previous Flippy climber, *E. robotica*'s locomotion control consists of attaching one gripper, flipping the body until the free, moving gripper senses a surface to attach to, attaching this second gripper, and finally detaching the first gripper. Two IR reflectance sensors on each gripper track its proximity to the surface. To make the system more robust to slippage and other errors, the robot preferentially attaches only after moving through a neutral position (See Fig. 5a). On-board accelerometers in each gripper sense the bending angle of the robot body.

The original Flippy robot could traverse flat surfaces in different orientations and inner angles less than 180°, but was unable to climb around outer corners and convex curves. Since the top of the robot when bent creates a convex curve, we used the geometric model from [16] to redesign the robot with a maximum outer body curvature of 220° and to traverse angles up to 230°, enabling the robot to climb over fellow robots, (e.g. in Fig. 3), no matter their configuration.

Physical Self-Assembly: To allow the robot to both climb by itself and attach to and climb over fellow robots, the robot uses the corkscrew grippers introduced in [16] and is covered in soft, stretchy Velcro loop (C). The gripper design, shown in Fig. 2 (F), uses four springs as corkscrews (H) which wind into the stretchable Velcro to form a connection. A motor controls the corkscrews via a simple gearbox drivetrain in an acrylic housing. To detach, the corkscrews run backwards, unwinding out of the Velcro, and the robot alternately attempts to flip, shaking itself free. The robot can attach and detach consistently with little noticeable wear on the Velcro surface of either the ground or other robots. To help the end effectors easily slide along the bumpy surface of other robots, we enclosed the gearbox within a plastic casing and run the corkscrews backwards - in the detachment direction - while the gripper is moving.

As shown in Fig. 2, Velcro is attached along the entire top and bottom portions of the robot, and secured at each rigid body segment. Unlike most modular robots which attach at specified docking points, *E. robotica* can attach to its fellow agents at any point along their body (e.g. Fig. 3), allowing for more structural configurations. Very few self-assembling or modular robots have this capacity, which is essential for making non-lattice-based structures. Other examples include FireAnt [17], another 2D climbing biped able to climb over models of itself, and Slimebot [15] which also uses velcro to make formations on a flat surface.

To self-assemble into structures, the robot adds one local control rule to its default flipping motion: if it detects

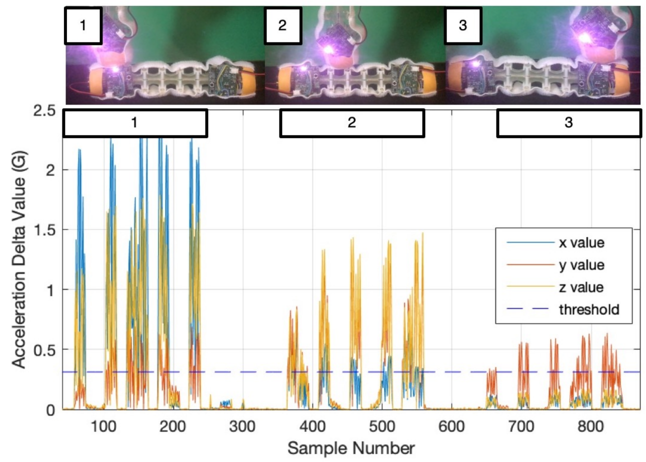


Fig. 4: Vibration pulse detection: A graph of the change in acceleration (delta) values for the detecting robot. Measurements are taken from bottom robot on the left side PCB; a vibration pulse is sent from a gripper attached at (1) the close end (2) the center and (3) the far end of the robot. Using the chosen threshold, the robot can detect pulses at any point along its body.

that another robot is climbing over it, the robot becomes stationary. As we demonstrate in simulation, this control rule allows for the formation of adaptive self-assembled structures. For this to be possible in hardware, each robot must be able to detect if another robot is climbing over it. Inspired by vibration systems in nature [5], *E. robotica* uses a vibration motor on each gripper to send pulses and signal its presence. When a robot attaches to another robot, the vibrations travel through the soft body and are recorded by the on-board accelerometers (MPU-9250). To detect vibration pulses, samples are taken of the change in (or simple derivative of) acceleration values; a large derivative value indicates that a pulse has been detected. An appropriate threshold value was chosen, which must be met for at least three samples before a robot considers itself stepped on, to reduce false positives and noise. Fig. 4 depicts the delta values for one of the accelerometers when a robot gripper is attached at the end closest to the sensor, in the middle of the robot, and at the far end. As shown in the supplementary video, the robot can detect each of these pulses using the given threshold.

Demonstration: In Fig. 3, we show video frames of one robot climbing across the body of a second robot (also in the supplementary video). Each time the climbing robot makes contact and attaches, it sends a vibration pulse, indicated by flashing pink LEDs. The bottom stationary robot detects that it is being walked over, and likewise uses pink LEDs to indicate that it has detected the vibration pulse of the top robot. This shows that a fully-autonomous and untethered *E. robotica* robot is able to climb over a soft, robot-made structure, and the robot inside the structure can consistently sense the presence of the moving agent. As we show in simulation, these are all of the ingredients necessary to create ant-inspired self-assembled structures. While we demonstrate these necessary self-assembly behaviors separately, *E. robotica* has not yet achieved the reliability in climbing necessary to implement self-assembly with multiple robots moving together. This is mostly due to solvable issues in construction - in particular, the delicacy of the tension switches and inconsistencies in the integration of the IR sensors. To realize our full algorithm in hardware, we are working to improve construction methods and the overall reliability of the robot.

IV. SELF-ASSEMBLY SIMULATION

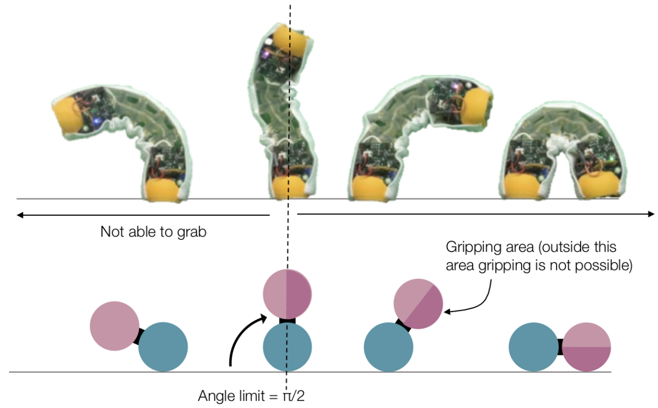
In this section, we demonstrate in simulation that a simple algorithm allows the *E. robotica* robots to self-assemble adaptive and dynamic structures. The algorithm, depicted as a state machine in Fig. 5b, consists of two states and relies on one main rule, i.e. robots stop moving if stepped over. Inspired by army ant bridges in both nature and prior experiments [4], we focus on assembling short-cut bridges across V shaped terrains and show that the algorithm creates bridges that adapt to traffic: At low traffic, no bridges form; as the traffic increases, bridges form and increase in size, smoothing the path and reducing congestion. As in the natural system, bridge shape and height is determined both by the traffic rate and the angle of the V-shaped terrain. When traffic is stopped, the bridge disassembles.

A. Simulation Environment and Robot Algorithm

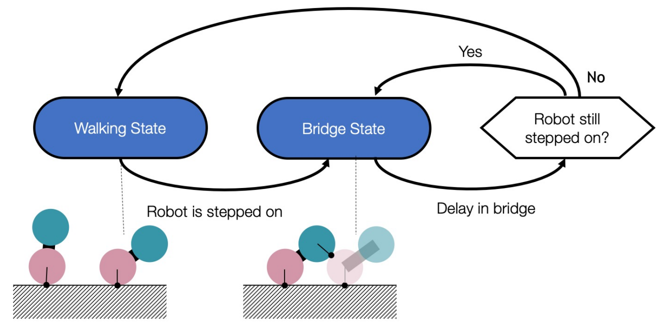
To simulate the effect of the self-assembly rules, we created an abstracted kinematic model of the *E. robotica* agents in the physics engine Box2D. The model captures the main characteristics of the real robot while also allowing computationally tractable simulations of hundreds of robots.

Simulated Robot Model: Like the system hardware, the simulated robot is a biped agent which moves with a flipping motion gate (Fig. 5). The two feet of the robot are modeled as rigid circles attached by a rectangular bar, and the flipping motion is produced by a rotating motor at each end of the bar. When the feet collide with a surface, whether the ground or another robot, they can grab by making a pin joint. The pin joint is compliant, approximating the compliance of real robots in hardware due to their flexibility.

The simulated flipping motion is likewise modeled after the real robot: When the robot starts flipping, it preferentially grabs only after passing through the neutral position. If the robot collides with ground or another robot before the neutral position, it has a random delay before grabbing, which is proportional to its angular distance from neutral. This allows



(a)



(b)

Fig. 5: a) Real robot and simulated robot flip and attach only after going through the neutral position. b) State machine for a simulated robot consists of two states: (i) the walking state where the robot continuously flips and moves forward, and (ii) the bridge state where the robot remains stationary as a result of sensing being stepped over.

the real and simulated robots to not prematurely grab if they slip or collide with another robot right after starting to move. A simulated robot can sense if it is being grabbed by another robot, implemented in the hardware system through the previously described vibration pulses. For simplicity, gravity and friction are not modeled, and the simulation is restricted to 2D to match the current robot system.

Simulation Environment and Parameters: Bridge formation and dissolution experiments were simulated on a vertical terrain with a V-shaped gap (Fig. 6), inspired by [4], which demonstrates *Eciton Hamatum*'s response to differently angled terrains. In our simulation, two sets of parameters defined the setup of each experiment: geometric parameters for the shape of the terrain and traffic parameters for the flow of robots. We considered symmetric V-shaped terrains of fixed height where the angle at the bottom is varied. Robots are created on the left of the terrain one after the other and move at a constant speed. The traffic flow rate is defined by the delay between creation of the robots, which determines the distance between the robots and their relative phase. Intuitively, in conditions of narrower V gaps or high traffic, one expects robots to collide more frequently and situations of congestion to occur. To generalize results, we

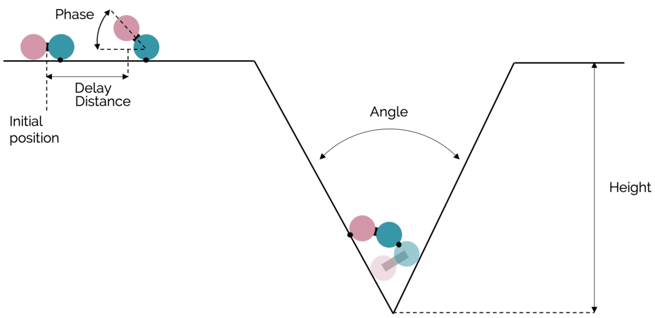


Fig. 6: Simulated experimental setup and parameters.

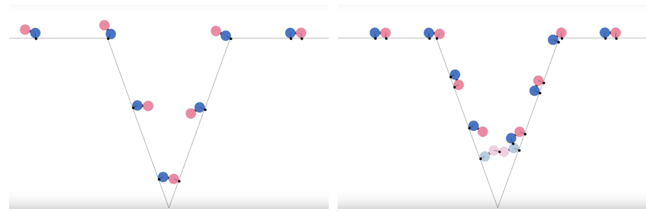
use the simulated robot body-length (BL) as the length unit. Time units are shown in seconds or flips; one robot flip period is equivalent to 1s (0.5s each for flip and wait time).

Algorithm: The simulated robots behave according to a simple robot algorithm (Fig. 5). At each point in time, a robot can be in one of two states: a walking state or a bridge state. Each robot starts in the walking state and keeps flipping until it is grabbed by another robot. When grabbed, the robot transitions to the bridge state and becomes stationary. A bridge state robot only transitions back to the walking state after it senses for a set time that it is no longer grabbed by any other robots. The Box2D simulator generates all of the collision events, so the dynamics of bridge formation emerge as a result of a series of collisions.

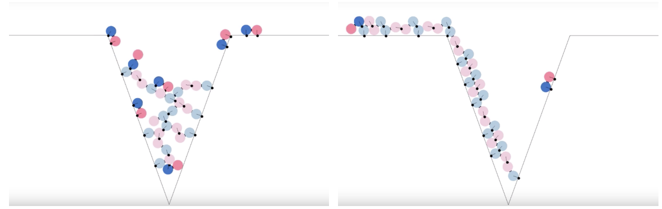
B. Experiments and Results

We studied the formation and dissolution of bridge structures across a variety of terrain shapes (i.e., V-shaped gaps of different sizes) and traffic rates (i.e., inflow rate of new robots). For each experiment, we modeled two phases (i) the formation phase, where new robots are created in the simulated environment, and we expect structures to form, and (ii) the dissolution phase, during which no new robots are created, and we expect structures to dissolve. The length of each phase (200s) was experimentally determined to be significantly larger than needed to observe robust structure formation and dissolution.

The V-shaped terrain height was fixed to 8 body-lengths (BL) and the gap angle ranged from 20° to 100° in increments of 5°. At 20°, the width of the top of the V is close to 2 BL, making collisions very likely even at the top of the gap, while at 100° even collisions at the bottom of the V become unlikely. Traffic rate is defined by the delay between creation of the robots, which determines the distance in body-lengths between the robots. The traffic was varied to six different rates by setting the mean of the Gaussian distribution to values ranging from 1.3BL to 3.8BL in increments of 0.5BL. Distance is measured between centers of robots: a 1.3BL traffic mean implies that robots are practically colliding even on a flat terrain, while at greater than 4BL, traffic generates no collisions. For each pair of terrain shape and traffic rate, a total of 10 experiments were run, summing up to a total of $17 \times 6 \times 10 = 1020$ simulated experiments.



(a) Low traffic, no bridge (b) Medium traffic, stable bridges



(c) High traffic, stable bridges (d) Too high traffic, stacking

Fig. 7: Bridge formation types, for multiple traffic rates

Four different bridge formation types were observed across all trials. Fig. 7 depicts the four different types for a single terrain (V-angle $40°$) under different traffic conditions (1.3BL to 3.8BL). In the case of low traffic, no collisions occur and no bridge is formed. As the traffic increases, robots start to collide and small bridges form. The small bridges have the effect of smoothing traffic and eliminating further collisions, and these bridges remain stable for the duration of traffic. At higher traffic levels, larger and more complex bridges form. A bridge can be stable (unchanging) for a duration of time and then grow due to a burst of traffic. We consider a bridge stable if no new robot enters the bridge state for 40s, the time required for a single robot to traverse to the bottom of the longest terrain. At very high levels of traffic, unstable situations occur which we define as stacking: robots collide almost immediately resulting in a traffic pileup that extends out of the V gap to the terrain start. In this case, the simulation is halted and a stacking condition is recorded. Intuitively this will occur when robots are introduced faster than they can move out of the way. Robots travel approximately 0.5 BL per flip, so any slow down at 1.3 BL distance (where grippers are less than one flip from each other) creates this stacking situation.

Overall bridge formation results across all terrains and traffic rates are shown in Fig. 8. Each column corresponds to a V-shape angle and each row corresponds to a traffic value (mean inter-robot distance). Black sections with no number indicate that no bridge was formed, while red signifies stacking. For the remaining cells, the gray shade represents the percentage of observed stable bridges over the ten repetitions of the experiment. The number in the cells is the average number of robots in the bridge across experiments. The results match the desired adaptive behavior seen in biology: for low traffic and easy terrains, no bridges form; for high traffic and narrow terrains, bridges form, and tend to stabilize traffic; bridge size is larger if the traffic is high. At the frontier between those two areas, not all the experiments lead to a bridge formation. For very high traffic,

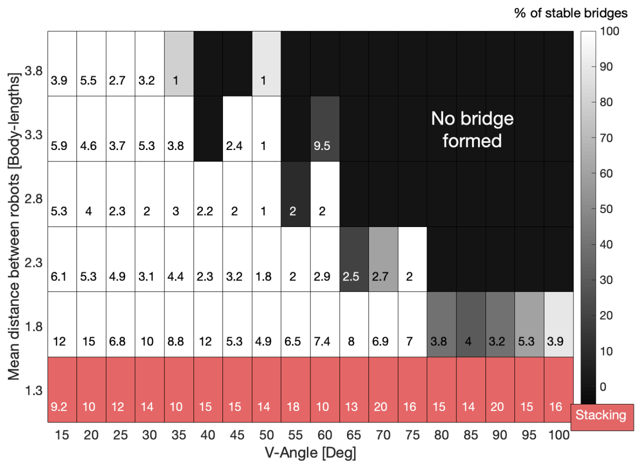


Fig. 8: Bridge formation across different terrain and traffic

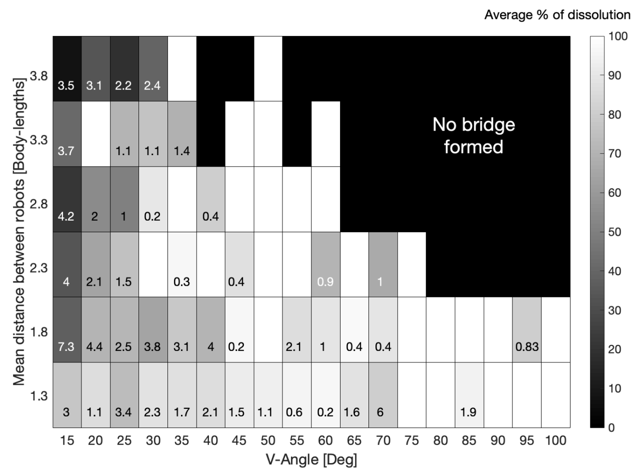


Fig. 9: Bridge dissolution across different terrain and traffic

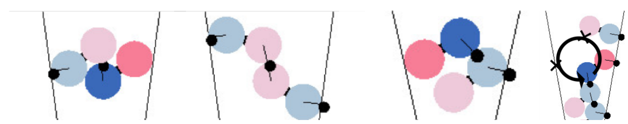
unstable pileups can occur (red cells), which has also been observed by the authors in experiments with army ants. Ants may solve pile-ups by finding or forming a wider path, which the current simulation does not allow.

Fig. 9 shows the results of bridge dissolution analysis for the same set of experiments. In the dissolution phase, the incoming traffic is stopped. Therefore, we expect that bridge robots at the top will no longer experience being grabbed by walking robots, and will therefore transition back to walking, exposing more bridge robots. As the results show, most bridges do completely dissolve. The gray shade represents the percentage of the bridge which dissolves, i.e. the percentage of bridge robots that leave after the flow of traffic ceases, averaged over ten experiments. The numbers in the gray boxes are the average number of robots stuck at the end of the dissolution step. In cases where dissolution is incomplete (73 out of 1020 experiments), only a few robots remain stuck in the bridge structure. Fig. 10 shows observed situations where bridges were unable to dissolve, caused by physical constraints such as when two robots grab each other (so neither can transition back to walking) or when walking robots become physically wedged into the terrain or bridge structure and are unable to move (Fig. 10c).

Finally, both formation and dissolution rules are not specific to the V-shaped terrain and can be used to self-assemble structures in more complex terrains with multiple ramps and gaps (see supplementary video and Fig. 1).

V. CONCLUSION

This paper presents *Eciton robotica*, a soft robotic hardware system for non-lattice -based, ant-like self-assembly. Robot agents are able to perform the necessary behaviors for self assembly; they can climb over each other and use vibration to sense the presence of other robots. To our knowledge, *E. robotica* is the first fully autonomous and untethered robot for self-assembly that is soft and flexible, and one of only a few which can form connections anywhere on its body, without the need for alignment.



(a) (b) (c) (d)

Fig. 10: Bridge dissolution failures: (a) A bridge robot grabbed from below (b) Two bridge robots grabbing each other (c) Walking (top) robot stuck in the terrain (d) Trapped walking robot which moves in circles

In simulation we show that simple local rules can induce robots to create structures which respond to terrain and traffic conditions. Simulated robots were able to form structures simply by joining the structure when stepped on by another robot; the majority of these structures were able to dissolve completely, while a few dissolved only in part. With the addition of more complex rules and communication, we expect all structures would be able to completely dissolve. Current experiments were limited to bridge formations over a V-shaped gap; in the future this could be expanded to show how the algorithm translates to other structures and formations such as ramps and towers.

Moving out of simulation, we are working to increase the reliability of the *E. robotica* agents in order to demonstrate a full version of the algorithm and form structures with multiple robots. In the future, we also plan to expand both our simulation and hardware system to 3D structures.

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SUPPLEMENTARY MATERIAL

Video available at: https://youtu.be/Dq6OuiH7aOM

References

[1] C. Anderson, G. Theraulaz, and J.-L. Deneubourg, “Self-assemblages in insect societies,” *Insectes sociaux*, vol. 49, no. 2, pp. 99–110, 2002.

[2] S. Powell and N. R. Franks, “How a few help all: living pothole plugs speed prey delivery in the army ant eciton burchellii,” *Animal Behaviour*, vol. 73, no. 6, pp. 1067–1076, 2007.

[3] S. Garnier, T. Murphy, M. Lutz, E. Hurme, S. Leblanc, and I. D. Couzin, “Stability and responsiveness in a self-organized living architecture,” *PLoS computational biology*, vol. 9, no. 3, p. e1002984, 2013.

[4] C. R. Reid, M. J. Lutz, S. Powell, A. B. Kao, I. D. Couzin, and S. Garnier, “Army ants dynamically adjust living bridges in response to a cost–benefit trade-off,” *Proceedings of the National Academy of Sciences*, vol. 112, no. 49, pp. 15 113–15 118, 2015.

[5] P. S. M. Hill, “Vibration and Animal Communication: A Review,” *American Zoologist*, vol. 41, no. 5, pp. 1135–1142, 2001.

[6] M. Yim, W.-M. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. S. Chirikjian, “Modular self-reconfigurable robot systems [grand challenges of robotics],” *IEEE Robotics & Automation Magazine*, vol. 14, no. 1, pp. 43–52, 2007.

[7] K. Gilpin, A. Knaian, and D. Rus, “Robot pebbles: One centimeter modules for programmable matter through self-disassembly,” *2010 IEEE International Conference on Robotics and Automation*, pp. 2485–2492, 2010.

[8] H. Kurokawa, K. Tomita, A. Kamimura, S. Kokaji, T. Hasuo, and S. Murata, “Distributed self-reconfiguration of M-TRAN III modular robotic system,” *The International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 373–386, 2008.

[9] F. Mondada, L. M. Gambardella, D. Floreano, S. Nolfi, J.-L. Deneuborg, and M. Dorigo, “The cooperation of swarm-bots: Physical interactions in collective robotics,” *IEEE Robotics & Automation Magazine*, vol. 12, no. 2, pp. 21–28, 2005.

[10] J. W. Romanishin, K. Gilpin, S. Claici, and D. Rus, “3D M-Blocks: Self-reconfiguring robots capable of locomotion via pivoting in three dimensions,” *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1925–1932, 2015.

[11] B. Haghighat, E. Droz, and A. Martinoli, “Lily: A miniature floating robotic platform for programmable stochastic self-assembly,” *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1941–1948, 2015.

[12] J. Davey, N. Kwok, and M. Yim, “Emulating self-reconfigurable robots-design of the SMORES system,” *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4464–4469, 2012.

[13] M. Rubenstein, A. Cornejo, and R. Nagpal, “Programmable self-assembly in a thousand-robot swarm,” *Science*, vol. 345, no. 6198, pp. 795–799, 2014.

[14] I. O’Hara, J. Paulos, J. Davey, N. Eckenstein, N. Doshi, T. Tosun, J. Greco, J. Seo, M. Turpin, V. Kumar *et al.*, “Self-assembly of a swarm of autonomous boats into floating structures,” *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1234–1240, 2014.

[15] M. Shimizu and A. Ishiguro, “An amoeboid modular robot that exhibits real-time adaptive reconfiguration,” pp. 1496–1501, 2009.

[16] M. Malley, M. Rubenstein, and R. Nagpal, “Flippy: a soft, autonomous climber with simple sensing and control,” pp. 6533–6540, 2017.

[17] P. Swissler and M. Rubenstein, “FireAnt: A Modular Robot with Full-Body Continuous Docks,” *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 6812–6817, 2018.