FireAnt: A Modular Robot with Full-Body Continuous Docks

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***Abstract*— Nature offers many examples of organisms coming together to form self-assembling structures. The attachment methods these organisms employ allow them to grab onto others' bodies, often without need for specific alignment or orientation, an ability absent from most existing robotic self-assembling structures, which require complicated sensing and specific alignment. This paper presents FireAnt, a modular 2D robot that demonstrates full-body continuous docks, an attachment mechanism able to attach anywhere onto other robots at any orientation, eliminating the need for alignment mechanisms and complex sensors. Such docks allow FireAnt to climb over copies of itself, something critical to self-assembling structures. This paper first discusses the design of FireAnt before presenting test results that show the strength and reliability of the continuous docks and demonstrate FireAnt's ability to traverse an environment consisting of inert FireAnt robots. The work presented in this paper provides a docking mechanism that can minimize the mechanical complexity of modular robots and will allow the creation of swarms of rigid and adaptable self-assembling structures.**

I. INTRODUCTION

One of the most fascinating behaviors exhibited by social insects is the ability of ants to build structures using their own bodies to enhance the capabilities and survivability of the swarm: ants form bridges to cross gaps [1], rafts to protect against floods [2], and bivouacs to serve as temporary nests [3]. Ants build these structures by climbing over each other and grabbing other ants at seemingly-arbitrary locations using their pincers or legs [2]. Similarly, cells use proteins at their surface to bond with neighbors [4], allowing an even-more diverse set of structures, including multicellular organisms. In contrast to ants and cells, which can attach to almost any point of another's body, the attachment mechanisms of existing robotic self-assembling structures almost-universally require alignment to specific docking locations.

Few robotic systems allow one robot to form an attachment to any point on a like body. The attachment systems of most modular [5] and structure-building robots [6] require features to ensure alignment to specific locations on like robots, necessitating sensors to align mating points [7] [8], or requiring magnets and other passive hardware to guide attachment [9] [10]. Even Swarm-Bot [11], which uses grippers to attach to a full-body ring on another robot, must first align its gripper, limiting the number and spontaneity of connections. These solutions increase dock complexity, constrain the end-structure to a rigid lattice, or both. One notable exception to these limitations is Slimebot [12], which uses genderless Velcro straps that allow any individual to connect to any other individual regardless of relative orientation and without need for alignment. A robust attachment mechanism with this ability would allow vast flexibility in the type and form of structures a modular robot could self-assemble and would eliminate the complexity of alignment between two robots. Unfortunately, attachments between Slimebots are too weak to build robust structures; such structures demand modular robots with strong docks.

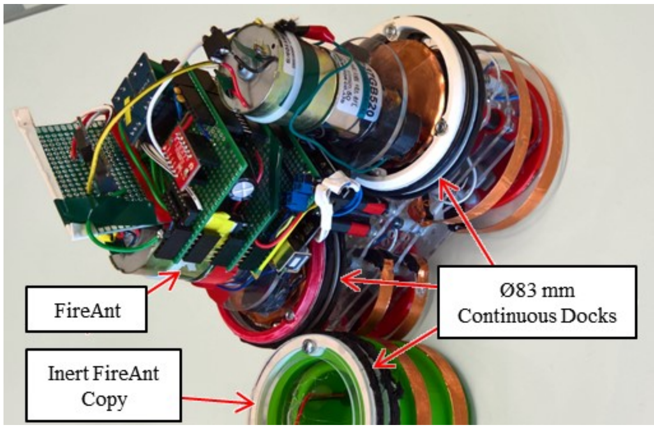

Fig. 1: FireAnt climbs atop an inert copy of itself by using its full-body continuous docks to rigidly attach to an arbitrary location along the dock's surface. These docks remove any need for robot-to-robot alignment before attachment.

Fig. 1 shows FireAnt, a 2D modular robot whose docking mechanism, the "continuous dock," allows for the strong, rigid connections found on many reconfigurable robotic platforms while also allowing the full-body, dock-anywhere flexibility of Slimebot. This paper demonstrates the strength and reliability of these continuous docks, as well as the ability of FireAnt to use these docks to traverse an arena made of inert copies of itself.

II. FIREANT DESIGN

The continuous docks are the most important part of FireAnt. As such, the docks drive much of the robot's design, defining its footprint, dictating its locomotion, and allowing FireAnt to function with only three sensors. The positioning of the continuous docks ensures that any approach by a geometrically-identical robot can only ever touch a continuous dock. The three main modules of FireAnt (see Fig. 2) stack out-of-plane to maintain this footprint. This design allows FireAnt to use these docks to traverse arbitrary arrangements of other FireAnt robots by using a flipping motion inspired by [13] and described in Fig. 3. The robot operates on test arenas inclined to an angle of 50° from horizontal, thus constraining the robot in-plane.

As configured, FireAnt weighs 1.1 kg and has a part-cost of $140.

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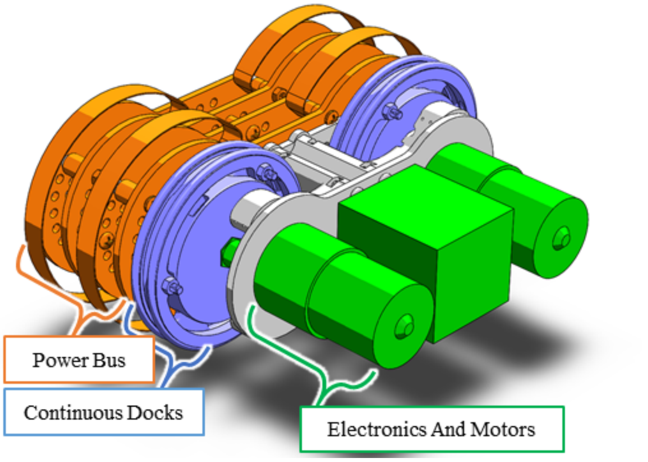

Fig. 2: The three major components of FireAnt (the power bus, the continuous dock, and its motors and electronics), stack such that any two robots coming into contact will do so on their continuous docks.

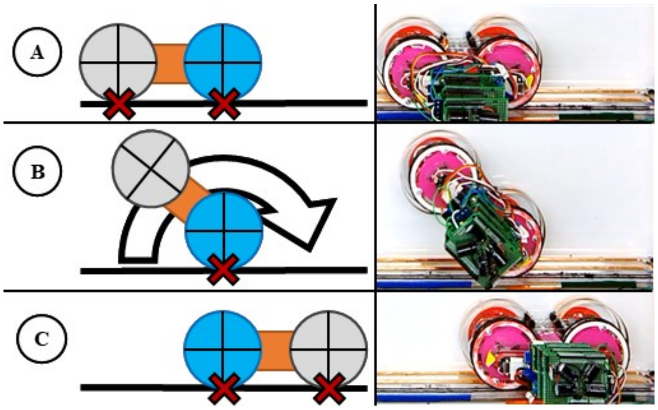

Fig. 3. FireAnt locomotes using a flipping motion. (A) The robot starts with both docks attached to the surface. (B) The aft dock (grey) then detaches from the surface and the robot flips by spinning the motor attached to the stationary dock (blue). (C) The robot flips until the newly-forward dock (grey) attaches to the surface. This process repeats as needed.

A. Continuous Docks

Fig. 4 details the continuous docks, which form rigid connections between FireAnt robots by melting together in a process similar to the solder attachments used by the modules described in [14]; these modules use a heating element to melt a Field's metal present on the docking surface. In contrast, the continuous dock uses Ø2.85mm strips of carbon-infused conductive plastic (PLA) as the bonding material. This removes the need for a separate heating element, since passing current through the resistance of the conductive plastic[1] warms and melts the strip, letting two such strips meld together.

A 20-gauge copper wire embedded within the conductive plastic allows FireAnt to apply a uniform voltage across the entire strip. When two such strips (energized to +24V and GND) touch, electrical current travels primarily along the negligible resistance of the copper wire until it reaches the area closest the contact point. Here, current must travel through the conductive plastic to reach the other copper wire. This method melts plastic only in the contact region with minimal heating of the surrounding material. Fig. 5 illustrates this process.

Connecting both dock voltages to GND stops current flow and allows the conductive plastic to cool, rigidly bonding the two strips of conductive plastic. To detach, FireAnt reapplies the voltage to again melt the plastic, weakening the connection, and allowing the two docks to separate. Since copper wire is present along the entire length of the dock, attachment between two docks can occur at any contact location, regardless of the positioning or relative orientations of the two docks.

Gluing the conductive plastic and copper wire assembly to a structural hoop forms a strong and rigid rim with a resistance of 100–300Ω between the copper wire and the outer diameter of the conductive plastic. Two such rims mount onto a wheel to form the completed continuous dock. The wheel has a copper plate to which brushes from the main body of the robot make contact, allowing FireAnt to apply a voltage to the continuous dock.

During attachment, FireAnt must (at minimum) ensure a connection strong enough to resist the stresses induced during locomotion. Therefore, a connection must achieve a large-enough interface area to mitigate this stress (stress decreases as area increases), and must achieve a temperature sufficient to melt and affix the two docks. Unfortunately, direct and precise measurement of the interface area and temperature of a connection would require a complex array of sensors. To avoid complexity, FireAnt instead uses one hall-effect current sensor per dock to estimate the quality of a connection attempt. Current is a heuristic for contact area: as interface area

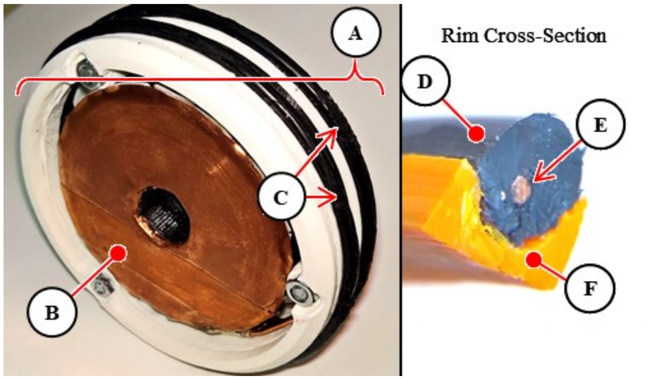

Fig. 4. A continuous dock (A) consists of a wheel to which FireAnt can apply a voltage (B) and two rims (C). Each rim consists of a Ø2.85mm strip of conductive plastic (D) containing an embedded copper wire (E). The plastic strip is glued to a structural hoop (F) to provide dock rigidity.

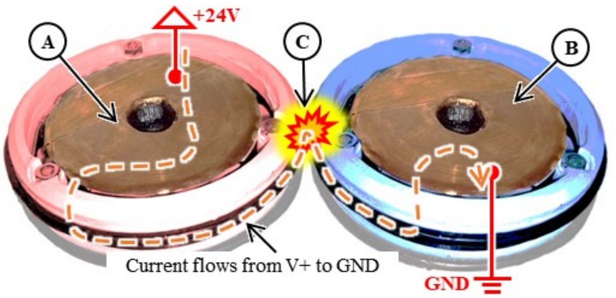

Fig. 5. The red wheel connects to +24V (A), and the blue wheel connectes to GND (B). The two come into contact, causing current to flow from the electrical-contact plate and through the copper core of the continuous dock until it reaches the point of contact (C). At this location, the electricity flows across the docks, melting the plastic.

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[1] The conductive PLA has a conductivity of 15 ohm-cm [12]

increases, resistance between the docks decreases, thus increasing current. The time-integral of the current is a heuristic for temperature: dissipated energy raises dock temperature and is proportional to the time-integral of the current. Iterative testing showed that current of 0.8A and an integrated current of 5.35 amp-seconds[2] yields a strong connection. After achieving attachment, the dock cools for two minutes to solidify the plastic into a strong bond (this conservative duration ensures thorough cooling).

B. Full-Body Power Bus

FireAnt does not use batteries due to concerns about power draw from the motors and continuous dock. Instead, the robot receives electricity through a power bus, as with [9] and [14], allowing a swarm of FireAnts to receive power from one powered robot. Similar to its full-body continuous docks, the FireAnt's power bus, shown in Fig. 6, allows power transfer regardless of contact location or orientation. The power bus consists of two electrically-connected pairs of circular, flexible, spring-steel rails covered in conductive copper tape. The rails are large enough to contact before the continuous docks touch, while still being sufficiently flexible not to push away other robots.

Other benefits to using a power bus compared to commercially-available battery packs are reduced weight and cost. Increasing weight is of particular concern since it would increase forces induced during locomotion, and any self-assembled structures would bear a greater weight. The power bus configuration also removes the need to recharge robots between experiments and simplifies the process of activating robots: the robots turn on once they are placed in the test arena.

C. Motors and Electronics

FireAnt uses an Arduino Uno as the platform for its electronics to allow easy hardware and software development. As seen in the high-level block-diagram in Fig. 7, all electronics receive power from the 24V supply of the power bus; the continuous docks use this voltage directly, while regulators and buck converters bring the voltage to a usable level for the Arduino and the motors respectively. A capacitor bank ensures that the Arduino does not restart if the power bus momentarily loses connection.

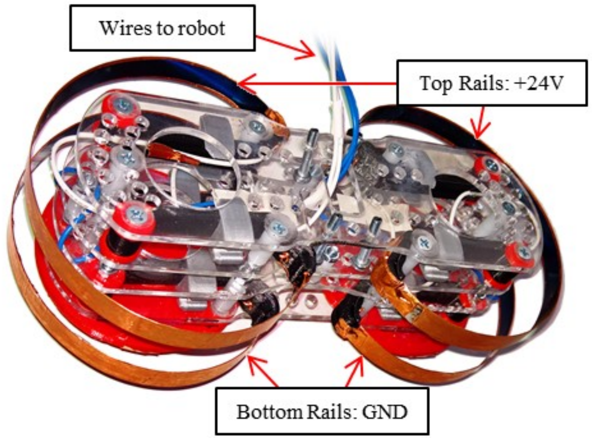

Fig. 6. The power bus transfers 24V DC power, which it recieves using its conductive rails, to the main body of FireAnt, powering the robot.

Motors attached to the continuous docks allow FireAnt to locomote by flipping about an attached dock. An accelerometer allows FireAnt to measure its rotational speed and control motor speed with a closed-loop proportional controller; this prevents the robot from flipping too quickly and slamming into the attachment surface (potentially breaking an attachment). These motors also press docks together during attachment with a force of 1.2 kg (110% of the robot's weight), and pull docks apart during disconnection.

FireAnt uses an H-bridge to control the continuous docks, tying them to GND, +24V, or a high-Z state[3]. A hall-effect current sensor measures current flow through the dock. This allows FireAnt to track attachment progress, and to detect when a dock at +24V contacts a dock at GND (current begins to flow upon contact). The sensor also allows closed-loop control of dock current via PWM control of the H-bridge.

Each of the three dock H-bridge states corresponds to different dock behaviors. A robot seeking connections can connect its dock to +24V, and a robot accepting connections can connect its dock to GND; current flows between two such docks when the two robots contact, allowing attachment to begin. If a robot does not wish to accept attachments (as may occur in swarm algorithms), the robot can force a dock into a high-Z state, preventing current flow between itself and a contacting dock, thus blocking any connections or disconnections.

FireAnt can also use its docks as a means of local communication between robots. Simple messages such as "I'm seeking a connection" (+24V), or "I'm accepting connections" (GND) are inherent in the voltage of the dock, and are received by a robot either through monitoring current flow (if at +24V or GND), or by monitoring the output of a comparator circuit (if in high-Z). Of course, since FireAnt can rapidly change the voltage level of the dock, more complex messages are also possible. To demonstrate this, we performed an experiment in which one dock sent a low duty-cycle, 24V, 100 kHz PWM signal to a touching (but not attached) dock. A microcontroller monitored the output of a comparator

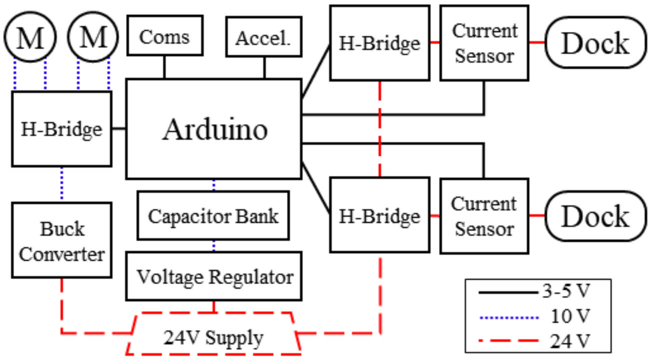

Fig. 7. The Arduino controls two motors and two continuous docks, receiving feedback from only three sensors (two current sensors and an accelerometer). The entire robot is powered from a single 24V supply, which it receives from the power bus.

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[2] At the 24V used for connection, this results in an energy transfer of 130J, 1% of the energy in a 1000 mAh one-cell Lithium polymer battery

[3] The locomotive demonstration shown later in this paper uses power MOSFETs control dock voltage due to overheating H-bridge chips in earlier tests. Future iterations will use more-robust H-bridges.

connected to the receiving dock, interpreting the signal without error. We conclude from this that robots will be able to send and receive messages using their continuous docks.

III. TESTING AND DEMONSTRATIONS

A. *Dock Strength Experiments*

Use of a single-axis test rig (see Fig. 8) allowed development of the continuous docks to precede FireAnt design. This rig can push and pull docks with a controllable force while also controlling current flow between the docks in a manner like that of FireAnt. Repeatedly attaching and detaching the docks allows characterization of the strength and reliability of dock attachments. The following tests use identical continuous docks as are present on FireAnt and were performed after finalizing the dock attachment parameters:

- Repeated 5 kg pull, random attachment location
- Repeated 5 kg pull, single attachment location
- Pull until breakage

In the first test, the rig presses together two docks with a nominal force of 750g. This mimics a scenario in which FireAnt is upside down and must push against gravity; earlier tests showed that lower compression forces increase failure rates, so this represents a worst-case scenario. The rig melts the docks together and cools them using the same integrated current and cooling time parameters as the FireAnt robot. The test rig then pulls the docks with a tensile force of 5 kg (about the weight of five robots), stops moving, and verifies that the docks can sustain this load for 60 seconds. After returning the docks to a zero-tension state, the test rig melts and separates them. This process repeats across 100 trials, with the test rig spinning the docks between trials to randomize the attachment location, as occurs in real-world robot locomotion. Across each of these trials, the attachment never failed, showing the real-world consistency of the dock.

The second test is identical to the first, except that the test rig does not spin the docks between trials, causing the docks to repeatedly attach at the same location. Once again, the attachment never failed across the 100 trials, reinforcing the consistency of the continuous dock.

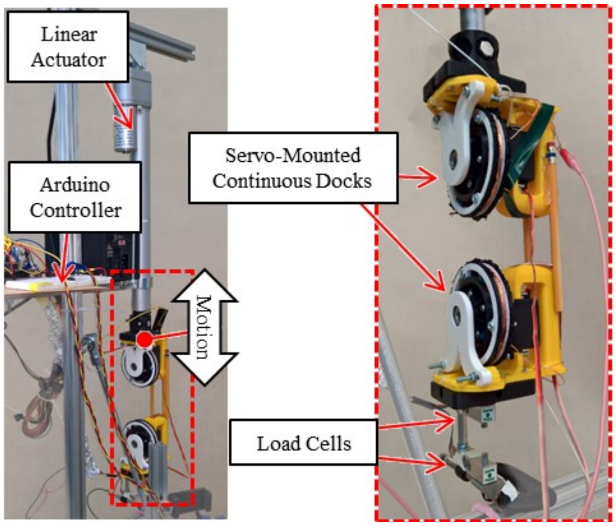

Fig. 8. The test rig uses a linear actuator to test the continuous docks through repeated attachment and detachment.

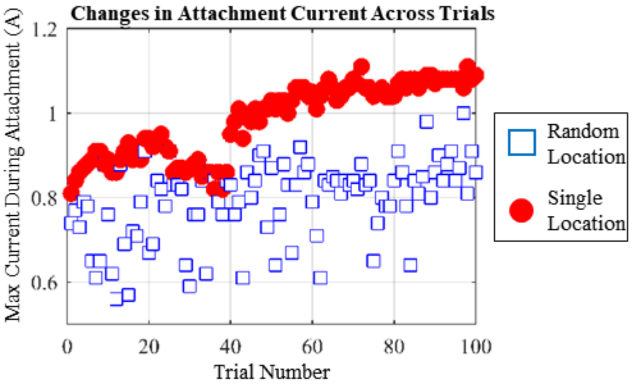

Fig. 9. Randomized contact locations result in highly variable maximum current during attachment, suggesting inconsistent contact area.

Although neither test experienced any failures, examination of the maximum current during attachment (Fig. 9) reveals differences between the connections formed in these two tests. Whereas the maximum current is generally consistent (gradually increases) for the single-location test, the attachment current for the randomized attachment test varies between trials. In the context of the interface area, these results suggest that the docks in the single-location test gradually conformed to each other, while the docks for the random-location test did not enjoy such advantages: high and low points would not necessarily match-up between trials, leading to suboptimal interfaces.

The final test characterizes the failure load of the continuous docks. Because dock failure load can exceed the maximum force possible on the test rig, we removed the docks from the test rig after attaching them in the same way as in the previous two tests, then hung them from a scale. This allowed manual application of a load sufficient to break the connection between the two docks. Across five trials, failure occurred between 17.3 kg and 28.8 kg, with an average failure load of 23.9 kg[4], more than 20 times the weight of the robot.

These tests demonstrate the high strength and reliability of the continuous dock.

B. *Dock Failure Modes*

Three common failure modes emerged during development and testing: spike formation, smoke, and tear-off.

Spikes grow from the surface of the conductive plastic when FireAnt prematurely pulls a warm dock away from its attachment surface, causing strands of plastic to pull away and harden. As seen in Fig. 10, the resulting spikes can double the height of the surface, making it difficult for FireAnt to achieve

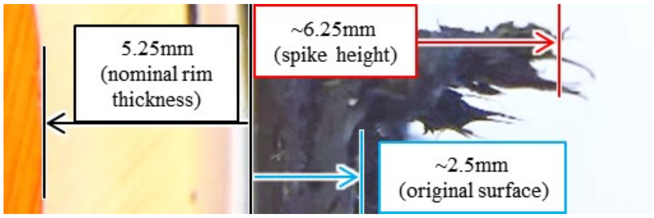

Fig. 10. Spikes on a continuous dock can prevent sufficient contact between two docks to form a strong connection.

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[4] Assuming a 35mm-long, rectangular contact area, the stress induced by a tensile force of 23.9 kg is equivalent to the maximum stress induced by a bending moment of 14 kg-cm, about 150% FireAnt's rated motor torque.

a strong connection at this location. Worse still, a large spike can jam the dock's wheel, making further locomotion impossible. FireAnt employs two techniques to avoid spike formation. First, the robot passes 9.5 amp-seconds through the dock (180% of attachment) before pulling it away to ensure that the detaching dock is very hot; spikes become thinner and thus weaker as temperature increases. Second, FireAnt spins its dock during detachment, which has the effect of pressing down any still-warm spikes, making future attachments easier and minimizing the risk of jamming the wheel.

The conductive plastic emits smoke when it reaches too-high a temperature. An attachment occurring under such conditions is often strong enough to use, but can sometimes be very weak. In extreme instances, the conductive plastic carburizes, limiting the strength of future attachments. A smoke failure often occurs when a segment of the conductive plastic is barely offset from the attachment surface, causing electricity to arc across the gap. To prevent this arcing, FireAnt presses the dock firmly against the attachment surface to close any small gaps. Another cause of smoke is simply allowing too much current to pass through the dock (this is the reason for the integrated current limit). Because a smoke failure can be so catastrophic, the integrated current limit is the only criterion FireAnt uses to decide when to turn off a dock and complete the attachment; using a minimum-current threshold as the criterion for a completed bond (current is a proxy for contact area) is untenable since there is no guarantee that the desired current will occur prior to a smoke failure. Fortunately, the high strength of the dock allows FireAnt to function even if it does not achieve the ideal minimum current of 0.8A.

Tear-off failures are sudden and tend to occur when FireAnt presses its forward dock into the attachment surface, inducing a bending moment at the rear dock and allowing the rear motor to tear the dock from its attachment. Most such failures result in a clean break and do not affect the ability of the dock to form new connections, though in one instance the dock tore off a piece of the attachment surface. Tear-off most often occurs when the prior attachment used a spiked portion of the dock, or after a small smoke event, highlighting the importance of the previously-described mitigation behaviors. Another cause of tear-off can be FireAnt flipping too quickly and slamming into the attachment surface, inducing a large dynamic load. FireAnt counteracts this by using a slow flip speed of 5.25 rpm.

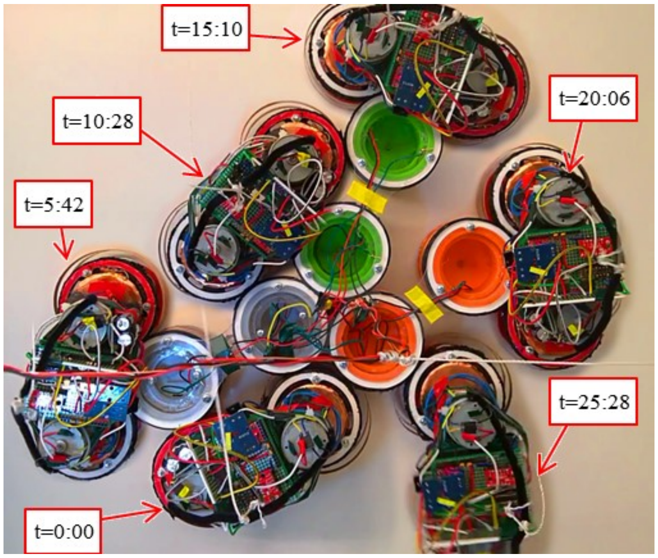

Fig. 11. A composite image taken during experiments in which FireAnt successfully navigated around a cluster of inert copies. The image shows a moving robot's location at various times. Power wires are brought out-of-plane, perpendicular to the arena so as to not impede FireAnt as it traverses the cluster.

C. Cluster Navigation

The main design goal of FireAnt is to use the continuous docks to climb over copies of itself, an ability critical to modular robots and self-assembling structures. As a demonstration of this capability, we constructed an arena consisting of three inert copies of FireAnt, pictured in Fig. 11, and tilted the arena to an angle of 50° from horizontal (the steepest angle allowed by FireAnt's center of gravity).

To traverse the arena, FireAnt executes the finite state machine shown in Fig. 12 to perform the flipping locomotion shown in Fig. 3. During execution of this finite state machine, the robot controls the dock current down to 0.8A, and controls the motor speed to allow for a soft contact when flipping. For the first attachment only, we hold one dock of FireAnt to let it push itself into the attachment surface. After this connection cools, the finite state machine enters the third step of its main loop and begins to flip.

In the first step in the main loop of the finite state machine, FireAnt decides which dock it will move (FireAnt simply alternates between the two in the case of this experiment). The moving dock then energizes itself and begins melting its connection.

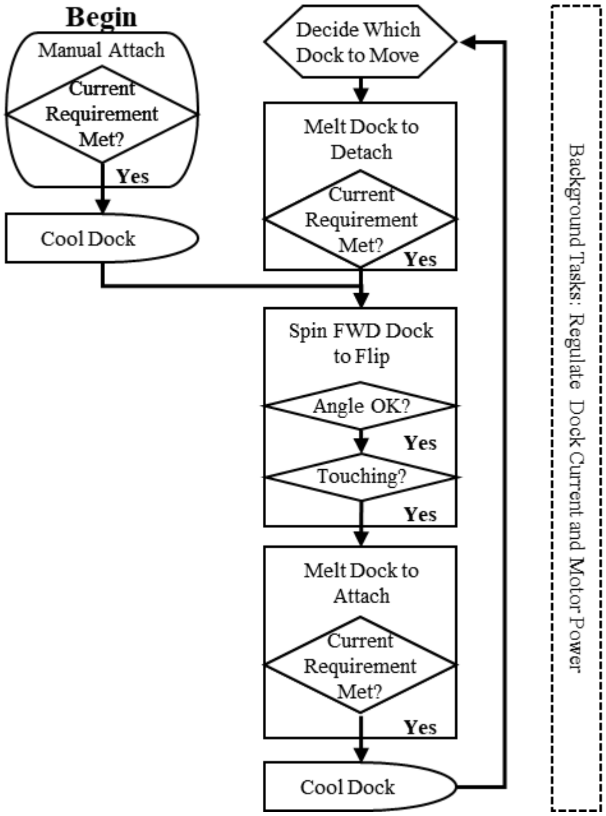

Fig. 12. The finite state machine governing FireAnt locomotion consists of five main steps. This results in successful traversal of arbitrary surfaces.

After the time-integral of the current reaches 9.5 amp-seconds, the motor attached to the stationary dock begins to rotate, lifting the now-molten surface of the moving dock away from its prior attachment. The moving dock also spins to mitigate spike formation. Once FireAnt flips 30° from its starting orientation (to guarantee disconnection), the moving dock stops spinning and FireAnt starts checking the current sensor of the moving dock; if current flows from the still-energized dock, FireAnt knows that the moving dock has contacted a robot that accepts attachments. FireAnt uses a touching-current threshold of 0.4A to ensure it has found a good attachment location. If FireAnt does not find a good attachment location in 30 seconds, it stops pressing the moving dock against the surface and briefly spins the moving dock to expose a different part of the conductive plastic. This attachment-seeking behavior repeats as necessary.

After finding a good contact location, FireAnt presses the moving dock into the attachment surface with the full power of its motor (about 1.2 kg of force). The moving dock then melts into the attachment surface until the time-integral of the current reaches 5.35 amp-seconds, after which the moving dock de-energizes. The newly-formed attachment cools for a period of 80 seconds while the FireAnt continues to press the moving dock into the attachment surface. A second cooling period of 40 seconds then occurs with all motors turned off, allowing the motor H-bridge and motors to cool. The finite state machine then repeats.

FireAnt completes a lap around this arena in 11 flips taking 28 minutes; the robot spends 80% of this time cooling after attachment. Although a shorter cooling duration would hasten locomotion, a conservative duration helps ensure proper attachment. In traversing this arena, FireAnt demonstrates its ability to move over copies of itself at any orientation (including upside-down) without the need for alignment mechanisms or complicated sensing.

IV. Conclusion

In this paper, we introduced FireAnt, a modular robot that uses continuous docks capable of climbing over arbitrary surface geometry, including groups of like robots, using only three simple sensors. The continuous docks allow the robot to form rigid attachments without the need for alignment or prior interaction with other robots. Tensile tests showed the capabilities of the continuous docks, and a demonstration of FireAnt's locomotive ability demonstrated the usability of these docks. In future work, such a robot will be able to cooperate with groups of like robots to form robust, non-latticed structures without need for complex sensing or alignment features. We plan to continue work on the FireAnt platform, iterating upon its design to allow for locomotion in a fully-vertical test arena, and in 3D. Such work will focus on further refinement of the continuous dock, improving its strength, reliability, and manufacturability through changes to its physical design. We also wish to investigate developing a specially-formulated plastic that could enhance the strength, reliability, and lifespan of a continuous dock. We hope to build a swarm of FireAnt robots and develop the collective behaviors that will allow the robots to build self-assembling structures.

The long melting and cooling times on FireAnt are due to the space and power constraints imposed by the robot design (attachment time was not a concern). A robot with different requirements and constraints could use a higher voltage to melt the plastic more quickly and could actively cool the attachment material. Recognizing the strength, reliability, and ease-of-use of the continuous docks, we hope that other research groups can make use of the work outlined in this paper to design their own robots; we believe that continuous docks can supplement or replace many existing attachment mechanisms.

V. Acknowledgment

We would like to acknowledge the contributions of Melinda Malley, David Becerra, and Radhika Nagpal for the initial conceptualization of the flipping locomotion and wheeled shape of FireAnt.

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