

Experimental Study and Modeling of Group Retrieval in Ants as an Approach to Collective Transport in Swarm Robotic Systems

This study finds that ants can act independently to accomplish complex tasks; application of models derived from ant behavior to robotic systems is investigated.

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ABSTRACT | Group food retrieval in some ant species serves as a useful paradigm for multirobot collective transport strategies that are decentralized, scalable, and do not require *a priori* information about the payload. We present a comprehensive overview of group retrieval in ants and investigate this phenomenon in *Aphaenogaster cockerelli* in order to extract the ants' roles during transport, the rules that govern their actions, and the individual forces that they apply to guide a food item to their nest. To measure these forces, we fabricated elastic structures with calibrated stiffness properties, induced ants to retrieve the structures, and tracked the resulting deformations with a camera. We then developed a hybrid system model of the ant behaviors that were observed in the experiments. We conducted simulations of the behavioral

model that incorporate a quasi-static model of planar manipulation with compliant attachment points. Our simulations qualitatively replicate individual ant activity as well as certain macroscopic features of the transport.

KEYWORDS | Biological system modeling; cooperative manipulation; distributed control; multirobot systems

I. INTRODUCTION

While there are various approaches to cooperative robotic manipulation, there are few completely decentralized approaches that are applicable to large groups of mobile robots. Such approaches may provide a greater degree of flexibility and robustness in construction and manufacturing applications. Cooperative food retrieval in ants is a striking example of a fully decentralized manipulation strategy that is scalable in the number of transporters and successful for a wide range of loads and environments. This biological phenomenon offers inspiration for the analogous problem in robotics: a group of robots is tasked to manipulate an arbitrarily shaped payload, which is too heavy for a single robot to move, to a target destination without *a priori* knowledge about the payload or obstacles in the environment. The robots must rely on local sensing and no explicit communication in order for the strategy to be scalable.

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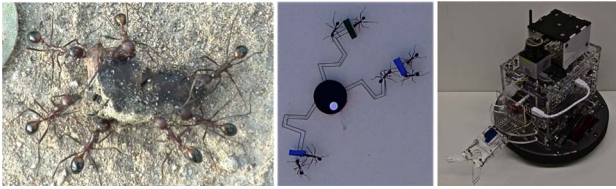


Fig. 1. From left to right: *A. cockerelli* ants retrieving a piece of fig and an elastic structure (springs are outlined for clarity), and a SCARAB differential-drive robot [41] equipped with a single-actuator gripper with passive compliance.

To extract the rules that govern ant transport behavior and better understand the mechanisms of successful collective transport, we study this phenomenon in *Aphaenogaster cockerelli* (Fig. 1), a monomorphic ant species that is common in the deserts of the southwestern United States. To the authors' knowledge, this is the first work that investigates the mechanics of cooperative transport in ants. We fabricate elastic two-dimensional structures that we use as vision-based ant force sensors and videotape ant retrieval of the structures. Using the video data, we quantitatively illustrate salient features of ant transport, including the emergence of consensus. We then develop a dynamic and behavioral model of ant transport in a step toward implementation on robotic platforms such as the one in Fig. 1. We validate the model by reproducing the observed characteristics of transport through simulations.

II. COLLECTIVE BEHAVIORS IN ROBOTICS

Tasks that require massive parallelism, a high level of redundancy, and adaptation to dynamic, possibly hazardous environments can potentially be performed very efficiently by a *swarm robotic system*. Such a system would consist of hundreds or thousands of autonomous, relatively expendable robots with limited sensing, communication, and computation capabilities. Taking inspiration from the composition of natural swarms such as social insect colonies, each member of the swarm or a large subset of the swarm is defined to be identical in hardware, unidentified, and programmed with the same set of control algorithms. As observed in natural swarms, this type of system may enable the parallel execution of tasks, robustness to individual failures, and ease of dynamically adding and removing individuals. A robotic swarm might also have the benefit of being economical, since the limited resources of swarm members imply a low unit cost.

Recent advances in embedded processor, sensor, actuator, and communication technologies are paving the way for the development of such systems. There has been a growing interest over the past decade in developing them for applications including environmental monitoring,

exploration, military surveillance and reconnaissance, battlefield and disaster-area communication, chemical source localization, mine detection, search-and-rescue, medical monitoring and treatment, micromanipulation, and nanoscale manufacturing [8]. The swarm paradigm is particularly useful at the micro- and nano-scale, in which robotic platforms will have extremely limited on-board capabilities.

The enormous populations of the systems under consideration makes it impractical to use centralized control approaches, which can provide globally optimal solutions and system performance guarantees but usually have complexity that is exponential in the number of robots [18]. Decentralized control approaches, although likely to result in suboptimal system performance, are scalable with the robot population. They are also implementable on robots with restricted capabilities, since they require only local information obtained via sensing and/or communication without knowledge of the global state of the system. It is possible to combine the scalability and robot autonomy of decentralized algorithms with the performance guarantees of centralized algorithms by reducing the complexity of the controller synthesis problem via hierarchical control architectures [52], which can facilitate explicit coordination among robots, or a broadcast control architecture [42] that allows a supervisory agent to task the swarm. An additional consideration in the control of robot swarms is the need to restrict interrobot communication, since bandwidth becomes a limiting factor in communication as the population size increases.

Decentralized controllers for robot swarms have been synthesized to produce various types of collective behaviors. Decentralized approaches to task allocation in swarms have been developed in which robots switch between tasks either spontaneously at predefined rates or upon interacting with other robots or environmental stimuli [1], [2], [6], [31], [34], [35]. Several of these approaches are inspired by the self-organized behavior of social insects such as ants. In addition, decentralized assembly systems have been designed in which modules bind through random collisions [5], [28], [30] or in which robots find parts and join them together to create a structure or an assortment of products [40], [59], [60].

To produce cooperative manipulation behaviors in multirobot systems, many approaches rely on centralized or leader/follower schemes that require knowledge of the load geometry and possibly the contact forces [46]. Several decentralized manipulation schemes have been developed for motion and force control of a payload by a fixed group of robots in an obstacle-free environment [4], [29], [37], [46], [53], [56]. Groups of two robots only were used for experimental verification [29], [46], [56], and [29] requires communication among platforms. Other decentralized multirobot transport approaches include object closure and caging, which compose the robot behaviors of

approach, surround, and push in order to geometrically enclose and move an object in a predictable manner [19], [48]. An ant-inspired decentralized approach to multirobot box pushing, in which robots switch between simple behaviors in response to locally sensed cues, is presented in [32].

III. COLLECTIVE TRANSPORT IN ANTS

A. Incidence and Advantages of Group Retrieval

Group retrieval of food has evolved independently several times in the ants, but it is developed to much higher levels in some species than in others [27], [45]. Indeed, many ants that are otherwise highly social show little or no skill at collective transport. Most of their food can be retrieved by single ants; larger items are dissected in place and retrieved in pieces. Even in those species where group transport is known, it is typically uncommon and poorly executed, with burdens moved in a slow, uncoordinated way [10], [25], [26], [43], [50], [55].

Only in a few cases have circumstances fostered the evolution of efficient cooperative transport. Among the more impressive examples are the group raiding species variously known as army ants, driver ants, or marauder ants [20], [21], [23], [44], [45], [49]. Their massive colonies can only be sustained by a large intake of fresh prey gathered by vast swarms of foragers that travel tens or hundreds of meters from the nest. This voracity places a premium on high rates of prey capture and efficient movement of large prey along extended supply lines. Cooperative retrieval helps with both goals. First, it reduces the need for in-place prey dissection, freeing up labor for hunting. More importantly, it allows the same weight of prey to be transported by fewer ants. This is because prey transport teams are superefficient, meaning that they can lift more weight per worker than solitary carriers [20], [22], [44] (Fig. 2).

The desert ant *Aphaenogaster cockerelli* is also particularly skilled at group transport, but the underlying reason is to escape competition rather than to maximize transport efficiency [26], [39]. Its relatively small colonies contain only about ten thousand workers, and its foragers generally work alone. It lacks the aggressive dominance of group raiders, and is readily displaced from rich food sources by other ants that recruit numerous defenders wielding chemical repellents. Rather than fight, *A. cockerelli*'s solution is rapid collective retrieval of large food items before these competitors can monopolize them.

B. Organization of Collective Retrieval Teams

The expert group retrievers have solved several challenges to effective team coordination. These include assembling a team at the prey discovery site, distributing the porters around the burden, coordinating their efforts so that they do not work against each other, negotiating

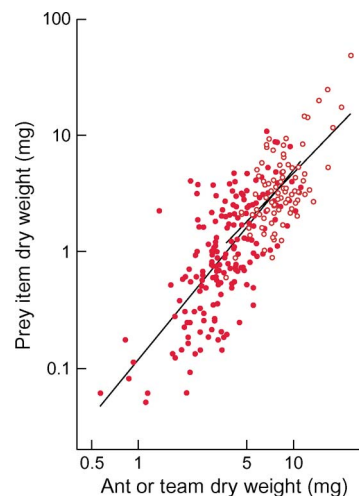


Fig. 2. Relationship between the dry weight of carriers and that of their burden for single porters (filled circles) and teams (open circles) of *Eciton burchelli*. The relationship for all data combined can be described by $P = 0.12A^{1.6}$, where P is item weight and A is ant weight ($r^2 = 0.62$, $p < 0.001$). The exponent is significantly greater than 1, indicating that the weight borne per ant increases with increasing ant (and team) weight. Data and analyses are from [20].

obstacles along the route, and dynamically dividing labor among the various subtasks of retrieval.

1) *Assembling a Retrieval Team*: In species that forage solitarily, the discoverer of a large food item must recruit distant nestmates to help her move it, using a species-typical communication method. Some use tandem runs, in which the discoverer returns to the nest and directly leads a single follower to the prey item [3]. In many other species, the discoverer deposits a chemical trail that recruits and guides a pulse of ants to the prey [17], [26], [50], [51], [54], [55]. Others rely on short-range recruitment in which the discoverer releases a volatile chemical that attracts nearby foragers [26]. In all cases, chemical signals, or pheromones, play a key role.

Some species, including *A. cockerelli*, use a sophisticated multistage approach that combines short- and long-range recruitment [24], [26], [57]. If an *A. cockerelli* forager finds a large prey item that she cannot move by herself, she runs about excitedly near the prey, frequently touching the tip of her abdomen to the ground [26]. This deposits a pheromone produced by the ant's poison gland, which can be detected by fellow foragers at distances up to 2 m. These respond by suddenly changing course and moving in a zig-zag pattern toward the pheromone source, where they join in attempting to move the prey and releasing more recruitment pheromone. Ants can enhance these chemical signals with chirping sounds made by rubbing the edge of one abdominal segment against a file-like ridged structure on the adjacent segment [39]. Ants

that detect these vibrations remain in the vicinity for longer, encircle the prey sooner, and release poison gland pheromones with greater likelihood. If these short-range signals do not attract an adequate corps of transporters, a forager will return directly to the nest, laying a trail of poison gland pheromone [26]. The trail is short-lived, but it can effectively summon a band of 5–10 transporters to prey 4 or more meters away.

2) *Matching Team Size to Prey Size*: Many species show a good match between prey size and the size of the retrieval team, ensuring that the prey is moved with maximum efficiency [20], [22], [44], [51], [57], [58]. For the most part, this arises in a self-organized way, without requiring ants to assess prey size and modulate their behavior. In army ants, for example, a team attracts new members only as long as it lags behind the pace of homeward bound traffic [20]. This simple rule prevents the colony from wasting effort on burdens that need no more help. Successful regulation of group size was confirmed by experiments in which transport teams were collected and their burden returned to the swarm. New teams soon formed, and their mean weight differed little from that of the original teams [20], [22]. In other ants, the key to team size regulation is the tractive resistance of the prey [17], [50], [55]. Ants initiate and continue recruitment only until the prey can be moved, ensuring that the population of potential transporters stops growing once enough are present. These rules also allow dynamic adjustment of team size with changes in terrain or difficulty of moving the burden [10], [49].

In most cases, prey size itself has no direct effect on individual behavior. Large piles of small prey items, each one of which is lifted easily by a single ant, fail to stimulate recruitment, but a small item that is pinned to the ground will do so [17], [50]. In *A. cockerelli*, on the other hand, there is some evidence of a direct influence of prey size [26]. **Trail-laying ceased to a single, waterlogged raisin bait once the population there reached 20–25 workers, even though the bait was pinned and thus still unmovable. If a larger bait was used, a larger number was summoned before recruitment ceased.**

3) *Handling the Burden*: In the group-raiding genera *Eciton* and *Dorylus*, team coordination owes something to their distinctive way of carrying their burden [20]–[23]. These exceptionally long-legged ants hold the load in their mandibles and straddle it, rather than carrying it towards the front or dragging it while walking backward (Fig. 3). This posture enhances stability by keeping the burden's center of gravity low and near to that of the ant. For large items, straddling also eases coordination of multiple carriers. They simply line up along the length of the item, all facing the same direction and thus driving the load in concert. Prey straddling is by no means necessary for effective group coordination, and indeed is uncommon

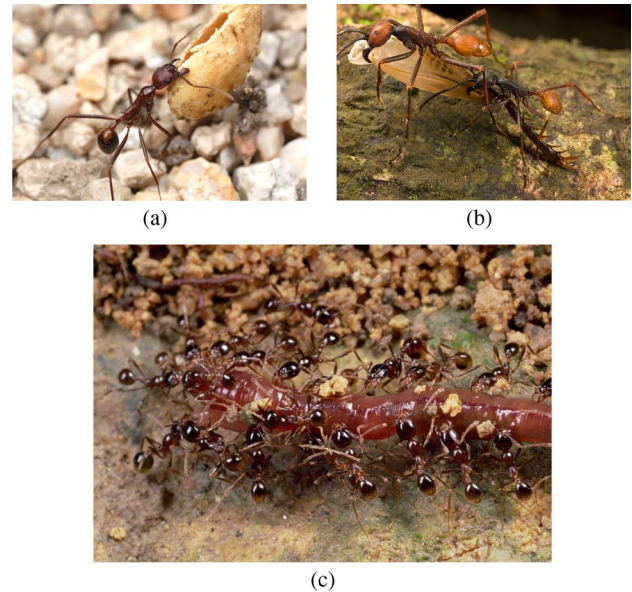


Fig. 3. Typical postures of individual and group transporters. (a) Solitary *A. cockerelli* transporters, like most ants, carry lighter burdens in their mandibles. (b) Groups of *Eciton burchelli* porters straddle their burden. (c) *Pheidologeton diversus* porters surround the burden and support it with their forelegs and open mandibles. Photo credits: (a) Alex Wild; (b), (c) Mark W. Moffett/Minden Pictures.

outside the army and driver ants. In most species, transport teams surround the burden while supporting it with their mandibles or forelegs [10], [26], [55]. This is the approach of the marauder ant *Pheidologeton diversus*, which otherwise shows similar group raiding and retrieval to that of *Eciton* and *Dorylus* [44], [45] (Fig. 3). As a result of their posture, the members of a retrieval team do not all adopt the same position and movement pattern: those in front walk backward and pull, those in the back walk forward and apparently push, and those on the side walk sideways, with bodies slanted in the direction of transport. Despite this, *Pheidologeton* teams achieve superefficient transport [44].

4) *Self-Organized Team Coordination*: Coordination of retrieval teams appears to be self-organized, rather than the product of team leadership. Retrieval begins with an uncoordinated period in which ants bite, lick, or tug at the prey, but little motion is seen [9], [54], [55]. This gives way, often quite suddenly, to steady movement toward the nest. Throughout this early period, ants frequently change the angle at which they are pulling, or seize the prey at a new location. At some point this yields sufficient force in the correct direction to initiate movement.

This kind of process also helps the group to deal with obstacles or changes in terrain. Ants respond to a hindrance by altering the direction or location of their effort until the item again starts moving [11], [55]. Similar behavior allows retrieval teams of *Pheidole oxyops* to spontaneously rotate

prey items when movement is easier in one direction than in another [16]. Frequent prey rotation requires flexibility in the roles played by individual ants. If an ant at the leading edge of the item is stopped by an obstacle, other team members may move ahead, rotating the object free of the obstacle, but also taking over the front-runner position. The ants must also be flexible about travel direction, as obstacles may require temporary detours from the straightest path to the nest [55].

For the most part, the behavior of ants in groups is much like that of solitary transporters [10], [12], [54], [55]. Coordination relies on indirect communication through the burden itself, rather than adoption of novel behavior in a group context. Still, there is some evidence for significant changes in behavior, as seen in the marauder ant *Pheidologeton diversus* [44]. When transporting alone, ants hold the burden in their mandibles. In a group, however, they lay their open mandibles on the burden without gripping it, and they use their front legs to help lift and steady it (Fig. 3).

5) *Teamwork and Division of Labor*: The ants in a retrieval team may play different roles, depending on their position within the group. The teams of *Eciton* and *Dorylus*, for example, have a distinctive composition, with a relatively large ant positioned at the front of the burden, and one or more smaller ants lined up behind her [21]. The large leader provides the bulk of lifting and propulsive power, while the smaller followers serve to prevent the load from dragging and to minimize rotational forces. Size sorting emerges partly because larger ants are more likely to first get heavy items underway; other ants then join until the load reaches the prevailing traffic speed. These followers are smaller than predicted if they are simply a random sample of available transporters, suggesting that larger ants actively avoid joining as second members [21].

Division of labor is a fundamental organizing principle of ant colonies, and is often associated with distinctive physical castes [27]. Group retrieval can be seen as a way of increasing colony flexibility by adding a plastic “supercaste” [20]. The new world army ant *Eciton burchelli*, for example, has a caste of large ants, the submajors, that are disproportionately involved in transport [20]. The old world *Dorylus wilverthi* lacks this caste, but makes up for this by relying much more heavily on transport teams of smaller ants [22]. These teams are likely less efficient than *Eciton*’s submajors, because the energy costs of transport decline with increasing ant size [47]. However, teams offer greater flexibility, including the ability to jointly carry very large items too big for even the largest ant.

6) *Orientation of the Team*: Successful retrieval requires that the team know which way to go, lest deadlock result from attempts to force the prey in different directions. It is conceivable that navigation is the responsibility of a subset of team members, with others following their lead.

However, the highly dynamic nature of retrieval, with frequent changes in the relative position and role of each ant, make it likely that all members must know the heading. For the virtually blind group raiders, a pheromone trail provides strong guidance toward the nest [20], [22]. For other ants, visual cues predominate, including landmarks that mark out a path and celestial compass cues used for path integration [14], [15]. Regardless of the cues used, the basic orientation strategy of all ant foragers is to always know the route leading back to their nest, which should aid the coordination of retrieval team members.

IV. EXPERIMENTS

A. Video Recording of Group Retrieval

Our experiments on collective transport in ants were performed in *A. cockerelli*’s natural Sonoran desert environment in South Mountain Park, Phoenix, AZ. Ants were induced to retrieve two elastic polydimethylsiloxane (PDMS) structures that were placed approximately one meter from an active nest entrance. Both structures consisted of a circular load ringed with several springs that were tipped with thin tabs. The design, fabrication, spring stiffness calibration, and modeling of the structures are described in [7]. The tabs at the ends of the springs were made attractive to the ants by smearing them with fig paste. The structures were placed on a flat wooden board (50 cm × 40 cm) lined with ivory copy paper. This provided a smooth surface across which the ants could drag the structures, as well as a featureless background to aid in automated video tracking. A high-definition video camera (Panasonic HVX200 or Canon HG20) was fixed above the structures on the vertical post of a copy stand. Its field of view encompassed a region of approximately 35 cm × 20 cm. A screen blocked direct sunlight from this region, to avoid shadows that could hinder video tracking. Fig baits in the vicinity of the structures were used to attract foragers. Once an ant discovered a structure, she soon initiated recruitment after unsuccessful attempts at moving it herself. A group of ants then cooperated to move the structure toward the nest.

B. Video Data Image Processing

In order to extract the structure configuration and the spring deformations from the video recordings of the transport, we tracked certain features of the structure, including the load and the tips of the springs. We covered the load with a black circular label marked with a small white circle offset from the center. Using SwisTrack [38], a general purpose vision processing software, we used thresholding and blob detection to label and track the load center and the dot. The load orientation was obtained by comparing the relative position of the centers of the dot and the load. If the orientation could not be determined for a particular time step, the corresponding data was disregarded because the load orientation is a key feature used to track the spring deformations. The bar on each spring

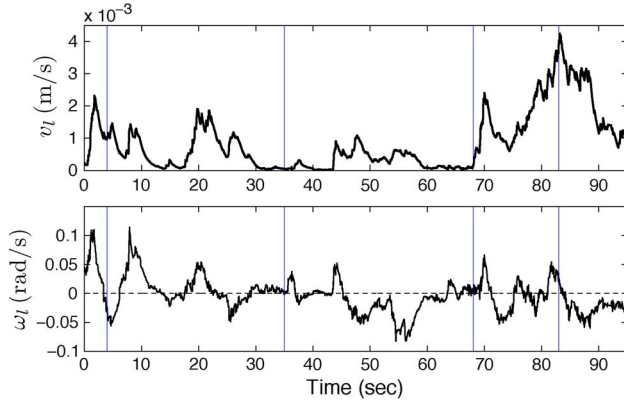


Fig. 4. Linear and angular load speeds over time for the trial in Fig. 5. Vertical lines indicate the times of the snapshots.

was marked with a red, blue, or green label and was tracked using similar methods. We calculated the deformation of a spring from the position of its label, the load pose, and other geometric quantities.

C. Results



1) *Mechanics of Transport*: We found that typical structure inertial forces were on the order of 10^{-4} mN, which was negligible compared to the friction force on the structures, $\mu mg = 32$ mN for structure 1 and $\mu mg = 22$ mN for structure 2, where the coefficient of friction $\mu = 1.4$ was measured from inclined plane tests with the structures. This indicates that the structures undergo quasi-static motion. The structures were often observed to move by stick-slip, which resulted in noisy data on load speed v_l . The average ant force $\|\mathbf{F}_i\|$ on structure 2 was calculated to be 10.5 ± 5.0 mN (sample size $n = 10906$); 99.1% of the samples did not exceed 30.0 mN.

2) *Cooperative Features of Transport*: We see evidence of an initial transport phase of low coordination among the ants followed by a more highly coordinated phase, as has been documented in the literature on group transport in ants (see Section III-B4). This phase transition is characterized by an increase in the linear speed of the load and a decrease in the sum of the ant interaction forces [33], each of which is defined as the projection of the difference in forces applied by two ants onto their relative position vector

$$\|\mathbf{F}_{ij}^{\text{int}}\| = (\mathbf{F}_i - \mathbf{F}_j) \cdot (\mathbf{r}_i - \mathbf{r}_j) / \|\mathbf{r}_i - \mathbf{r}_j\|. \quad (1)$$

This quantity is a measure of the degree of cooperation between two ants; it is zero when ants are perfectly cooperating.

We performed 9 trials with structure 1. Fig. 4 shows an instance of an increase in the linear load speed for one of the trials. The structure initially moves slowly on average, and then its speed sharply rises to significantly higher values at $t = 68$ s. Snapshots of the recorded transport and a plot of the evolution of the load configuration in Fig. 5 reveal that the transition between these phases of speed is initiated by the ants' reorientation of the structure, which they subsequently transport in a new direction.

We performed 18 trials with structure 2. Fig. 6 displays a phase transition that is characterized by a sizable reduction in the sum of the ant interaction forces for one of the trials. This sum decreases to about half its initial value on average after $t = 32$ s. In the snapshots in Fig. 7, this increase in cooperation is evident from the reorientation of the ants' bodies at $t = 42$ s, which occurs during the second phase, such that they pull with larger force components in the positive x direction toward the nest.

It is possible to provide a mechanics-based justification that an increase in load speed should be accompanied by a

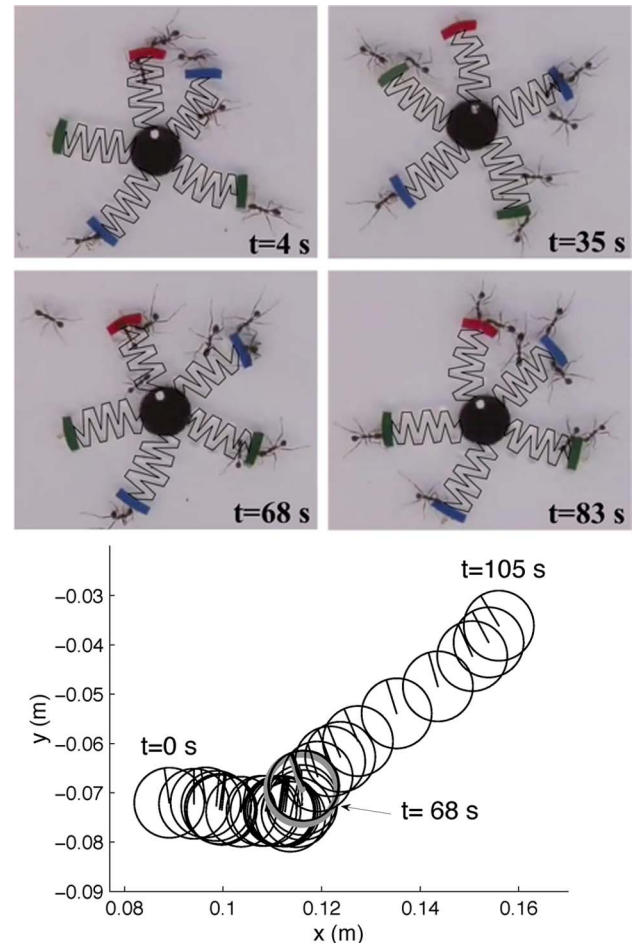


Fig. 5. Snapshots of ant transport with structure 1 (top); load position and orientation (bottom). The structure springs are outlined for clarity. The thick gray circle in the bottom plot signifies the load at $t = 68$ s.

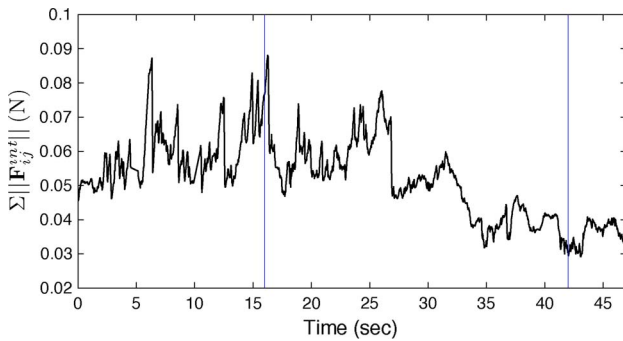


Fig. 6. Sum of interaction forces over time for the trial in Fig. 7. Vertical lines indicate the times of the snapshots.

decrease in the sum of the interaction forces, which implies less antagonistic actuation through a more cooperative arrangement of applied forces. However, while we observed one or both of these trends in each of the trials with structure 2, the data do not support any conclusions that we might be tempted to draw about their temporal correlation. This is because the dynamics of the elastic structure are significant and stick-slip friction often halted its progress, in effect reinitializing the structure repeatedly in the uncoordinated phase. A more systematic evaluation of a transported structure with reduced friction is required to experimentally establish a correlation between the two observed features of the transition to the coordinated phase.

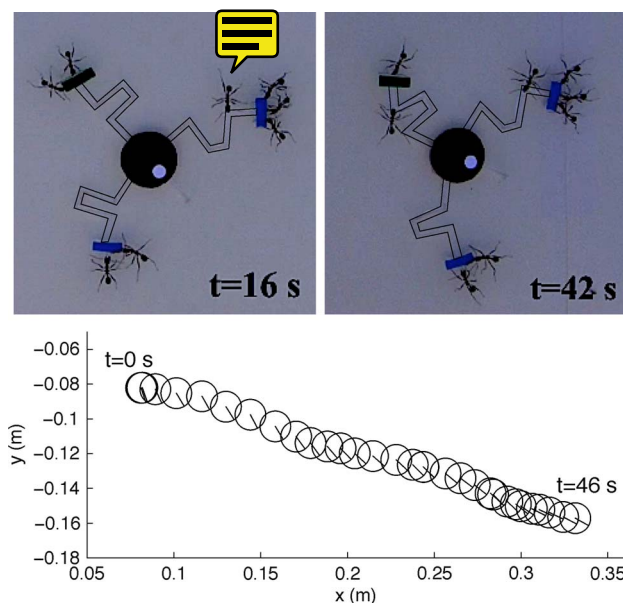


Fig. 7. Snapshots of ant transport with structure 2 (top); load position and orientation (bottom). The structure springs are outlined for clarity.

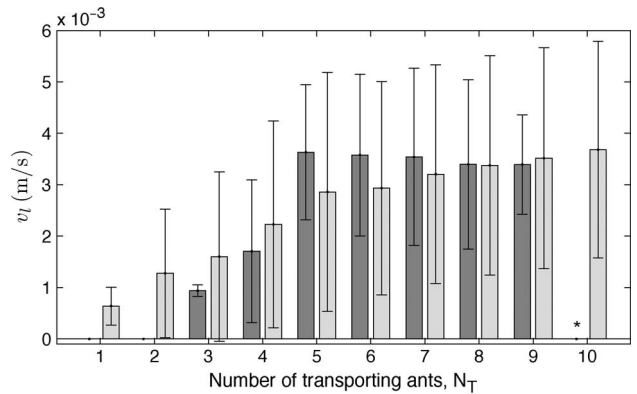


Fig. 8. Average load speed as a function of transport group size in the 18 experimental trials with structure 2 (dark gray bars) and the 30 simulation trials (light gray bars), which are described in Section VII. Error bars show standard deviations. Experiment sample sizes for $N_T = 4 - 9$ are $n = 561, 453, 4154, 2448, 1866, 182$; data for $N_T = 1 - 3$ were obtained manually, and * indicates that no data were available. Simulation sample sizes for $N_T = 1 - 10$ are $n = 1186594, 19971, 50522, 36362, 35459, 4956, 17700, 38777, 46289, 19234$.

3) Load Speed Saturation With Increased Group Size:

Fig. 8 shows that three ants are needed to move structure 2, and that when more than five ants participate in transport, there is on average no increase in the load speed. This is likely due to increased interference between ants during transport with higher populations.

V. DYNAMIC MODEL OF COOPERATIVE MANIPULATION

In order to simulate realistic motions of the elastic structures that are caused by the ants, we use a planar manipulation model that predicts the motion of an object similar in construction to the structures. This model is described in detail in [7]. In developing the model, we assume quasi-static motion, which was justified experimentally in Section IV-C1. In addition, we require that friction forces on the springs exceed the spring restorative forces so that a deformed spring cannot, in the absence of ants, cause the entire structure to move. We model each spring as a composition of an extension spring with spring constant κ_p and a rotary spring with rotational torque constant κ_r . To model friction, we use a three-point-contact support approach similar to the one in [13]. The motion of the load is determined by solving a maximum-minimum optimization of the instantaneous power that results from the friction forces and the forces and moments caused by the spring deformations.

VI. BEHAVIORAL MODEL

We developed a model of the ant transport behavior from qualitative observations of the videos of transport trials.

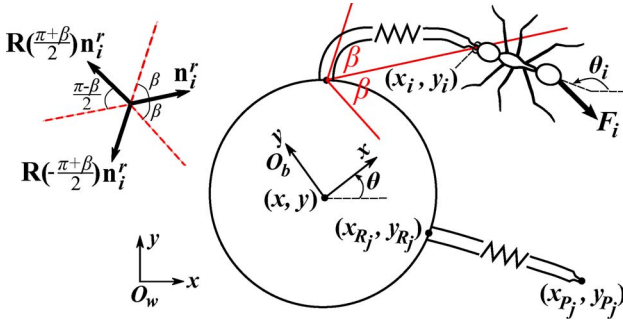


Fig. 9. Notation used in Section VI for a simulated elastic structure with a transporting ant (two springs are shown).

The transport strategy is represented as a hybrid system with probabilistic transitions between task modes. Fig. 9 illustrates the notation that we use in describing the model.

We represent each of a population of N ants as a point-mass agent governed by a kinematic model

$$\dot{\mathbf{q}}_i = \mathbf{u}_i \quad (2)$$

where $\mathbf{q}_i = [\mathbf{r}_i \ \theta_i]^T = [x_i \ y_i \ \theta_i]^T$ denotes the position of a point associated with ant i and the ant's orientation, both in the inertial frame O_w , and $\mathbf{u}_i = [u_i^x \ u_i^y \ u_i^\theta]^T$ is the vector of control inputs. We define the control inputs according to our observation that the motion of an ant during the transport trials resembles that of a unicycle much of the time.

We model the ants as switching between two behavioral modes, each corresponding to a different \mathbf{u}_i . In the behavior *Search for grasp point*, an ant i moves toward the structure in search of a protrusion to latch onto with its mandibles. If the outermost tip of a spring enters the sensing range of the ant and the spring is not already occupied by another ant, the ant latches onto the spring with probability p_1 . Once attached, the ant is in the *Transport mode* and pulls on the spring in a manner that directs the structure toward its estimate of the nest. The ant reverts to mode *Search for grasp point* with a probability per time step $p_{2,i}(\mathbf{F}_i(t))$, where $\mathbf{F}_i(t)$ is the force that the ant applies to the spring at time t . We defined this parameter as a sigmoid function of $\|\mathbf{F}_i(t)\|$ in order to reflect an ant's tendency to occasionally lose its grip or lose interest when deflecting the spring by a small amount and to release the spring more often as it exerts forces near the maximum force that it can apply. Defining F_m as a force close to this maximum and ζ as a positive constant, we set

$$p_{2,i}(\mathbf{F}_i(t)) = \left(1 + e^{-\zeta(\|\mathbf{F}_i(t)\| - 0.5F_m)}\right)^{-1}. \quad (3)$$

Raising ζ increases the slope of the sigmoid at $\|\mathbf{F}_i(t)\| = 0.5F_m$ and brings $p_{2,i}(\mathbf{F}_i(t))$ closer to 1 at the maximum force, which can be measured experimentally from the spring deflections. The ants stop moving when $\|\mathbf{r} - \mathbf{r}_n\| \leq \rho$, where $\mathbf{r} = [x \ y]^T$, the center of the structure, and $\mathbf{r}_n = [x_n \ y_n]^T$, the position of the nest, for some small constant ρ .

A. Search for Grasp Point

We define v_i and ω_i as the forward linear and angular speeds, respectively, of ant i . An ant's estimates of the structure position (x, y) , given by (\hat{x}, \hat{y}) , are defined as values of the random variables $\hat{X} \sim \mathcal{N}(x, \sigma^2)$ and $\hat{Y} \sim \mathcal{N}(y, \sigma^2)$, where σ^2 is a specified variance. These values are updated at each time step. The ant's desired orientation θ_i^d is defined as the angle of the vector from (x_i, y_i) to (\hat{x}, \hat{y}) . A proportional controller is used to steer the ant's orientation to θ_i^d

$$\omega_i = ke_i^\theta, \quad e_i^\theta = (\theta_i^d - \theta_i) \in [-\pi, \pi]. \quad (4)$$

A feedback linearization scheme is used to relate v_i and ω_i to the linear velocities of (x_i, y_i) . Hence the control inputs are

$$\begin{bmatrix} u_i^x \\ u_i^y \\ u_i^\theta \end{bmatrix} = \begin{bmatrix} \cos \theta_i & -r \sin \theta_i \\ \sin \theta_i & r \cos \theta_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ \omega_i \end{bmatrix} \quad (5)$$

where r is a small offset distance along the longitudinal axis of the ant. The resulting motion reproduces the slight oscillations that the ants displayed while searching.

B. Transport

An ant i in this mode is grasping the tip of spring j . The ant pulls on its attachment point, whose coordinates are given by $(x_i, y_i) = (x_{p_j}, y_{p_j})$, with a force \mathbf{F}_i . Let \mathbf{n}_i^f be the unit vector in the direction of this force. Also define \mathbf{n}_i^n as the unit vector from (x_i, y_i) toward the nest coordinates, (x_n, y_n) , and \mathbf{n}_i^r as the unit vector from (x_{R_j}, y_{R_j}) , the midpoint of the arc where spring j is attached to the load, to (x_i, y_i) . The angles of these vectors in the inertial frame are $\theta_i + \pi$, θ_i^n , and θ_i^r , respectively. To navigate to their nest (i.e., determine θ_i^n), ants use the strategies discussed in Section III-B6.

We observed that an ant grasping a spring will attempt to rotate the load into an orientation in which the ant can pull it while walking backward toward the nest. To emulate this behavior, which has also been noted in [55], we specify that at each time t , the ant can begin to reorient itself to any angle between $\theta_i^{\min}(t) = \theta_i^r(t) - \beta$ and $\theta_i^{\max}(t) = \theta_i^r(t) + \beta$. The angle β is upper bounded by

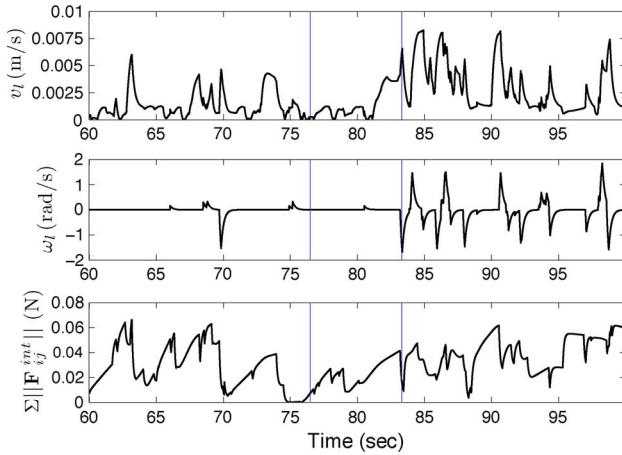


Fig. 10. Linear and angular load speeds and sum of interaction forces over time for the simulated trial in Fig. 11. Vertical lines indicate the times of the snapshots.

$\pi/2$ to preclude the situation in which the ant is standing on the spring while gripping the tab. Similar to (4), a proportional controller steers θ_i

$$\omega_i = k e_i^\theta, \quad e_i^\theta = (\theta_i^d - (\theta_i + \pi)) \in [-\pi, \pi]. \quad (6)$$

Fig. 9 illustrates a division of the plane into three regions that are bounded by light dashed lines; in the diagram, $\mathbf{R}(\theta)$ is the 2-D rotation matrix. The desired orientation θ_i^d at a given time depends on which of the regions contains \mathbf{n}_i^n

$$\theta_i^d = \begin{cases} \theta_i^n, & \text{if } \mathbf{n}_i^r \cdot \mathbf{n}_i^n \geq \cos \beta \\ \theta_i^{\max}, & \text{if } \mathbf{R}(\frac{\pi+\beta}{2}) \mathbf{n}_i^r \cdot \mathbf{n}_i^n \geq \cos \frac{\pi-\beta}{2} \\ \theta_i^{\min}, & \text{if } \mathbf{R}(-\frac{\pi+\beta}{2}) \mathbf{n}_i^r \cdot \mathbf{n}_i^n \geq \cos \frac{\pi-\beta}{2}. \end{cases} \quad (7)$$

The control inputs are defined as follows:

$$\mathbf{u}_i = [-v_i \cos \theta_i \quad -v_i \sin \theta_i \quad \omega_i]^T. \quad (8)$$

VII. COLLECTIVE TRANSPORT SIMULATION

We simulated transport scenarios with different numbers of ants and springs on the elastic structure. The configurations of the structure and the ants are updated at each time step using the dynamic manipulation model in Section V and the behavioral model in Section VI. The simulated structure, modeled after structure 2, has a mass of 1.6 g, a load radius of 8.83 mm, and springs with free

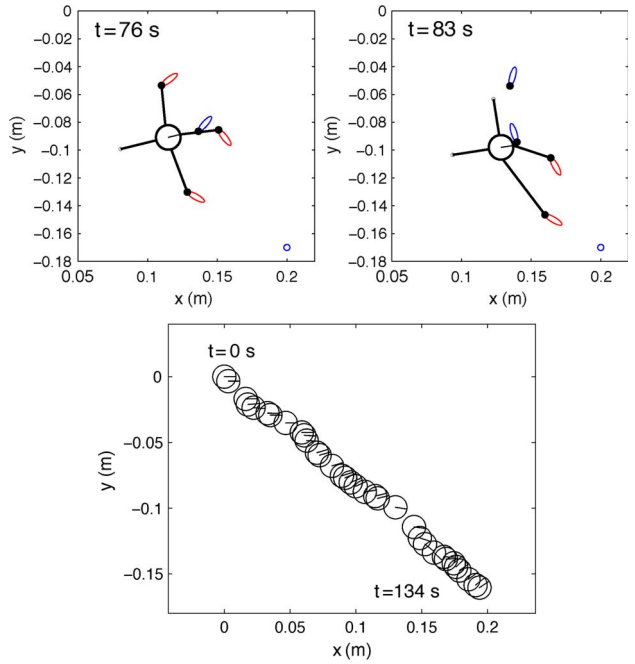


Fig. 11. Snapshots of simulated ant transport (top two plots); load position and orientation (bottom). In the top two plots, blue ants are in Search for grasp point mode, red ants are in Transport mode, and the nest is indicated by a blue circle.

length 2.63 cm, $\kappa_\tau = 4.52 \times 10^{-4}$ Nm/rad, and $\kappa_\rho = 0.664$ N/m; the spring constants were obtained from the spring model in [7]. The coefficient of friction was set to the experimentally determined value $\mu = 1.4$. We selected $p_1 = 0.2$, $\beta = 60^\circ$, $\zeta = 100$, $k = 10 \text{ s}^{-1}$, $r = 2 \text{ mm}$, and $\sigma^2 = 0.01$ to qualitatively emulate the observed ant behavior and $F_m = 20 \text{ mN}$ to achieve a maximum ant force near the experimental value of $\sim 30 \text{ mN}$ (see Section IV-C1). The ants initially have uniformly randomly distributed positions and orientations. All ants start in Search for grasp point mode, in which they move at $v_i = 0.08 \text{ m/s}$, which was estimated from video data. The nest is located at $(0.2 \text{ m}, -0.17 \text{ m})$.

Fig. 11 shows snapshots of a simulation run with four ants and four springs and the resulting load trajectory and orientation, and Fig. 10 gives the corresponding load speeds and the sum of interaction forces over time. We also conducted trials with one ant and one spring, five ants and ten springs, and ten ants and ten springs, performing 30 runs in total. The ant applied forces and interaction force sums and the load speeds measured from the simulations were comparable to the experimental values. In the simulations, the average ant force $\|\mathbf{F}_i\|$ was $5.0 \pm 5.1 \text{ mN}$ and the maximum force was 36.5 mN (sample size $n = 520057$). The sum of the interaction forces in Fig. 10 varies over a similar range to the sum in Fig. 6. Fig. 8 shows that the simulations produced average v_i that were fairly close to the observed speeds for $N_T = 3-9$. In addition, the figure illustrates that the simulations

reproduce the effect of diminishing increases in average v_l with larger transport populations, although the speed may not have saturated yet at $N_T = 10$.

The simulations replicate not only the successful transport of the structure to the nest, as shown by the trajectory in Fig. 11, but also the distinctive property of a phase transition to a higher degree of coordination among individuals. The load speed in Fig. 10 displays a similar trend to the experimental v_l in Fig. 4: a phase of low average speed with relatively small peaks is followed by a phase of increased speed. While the sum of the interaction forces in Fig. 10 does not obviously signal the phase change as it does in Fig. 6, it displays a sharp reduction around $t = 83$ s that coincides with the jump in v_l . The snapshots in Fig. 11 show that at this time, the transporting ants are arranged in a more cooperative pose than at the selected time in the first phase, a rearrangement that is evident in the snapshots of the experimental trials at times of low and high coordination as measured by the load speed or sum of interaction forces.

VIII. CONCLUSIONS AND FUTURE WORK

We have presented a study of the mechanics of cooperative prey retrieval in *A. cockerelli* ants based on experimental trials with vision-based force sensors. The experimental data show that this distributed transport system is characterized by an initial disordered phase that transitions to a coordinated phase of increased load speed and a higher degree of cooperation among the transporters, as well as a plateau in the progress of the task after a threshold population is reached. We developed a quasi-static dynamic manipulation model and an ant behavioral model based on observations and incorporated these models into a simulation that replicates the experimental phenomena. Our model of ant transport can be used to define fully decentralized controllers for cooperative manipulation in a multirobot system.

One avenue of future work is a continued study of collective transport in ants and refinement of the ant behavioral model. Further experiments can be conducted to extract the ants' changing roles, examine the mechanics of lifting during transport, and investigate the role of sustained interaction forces in helping to avoid obstacles and overcome deadlocks. We can also compare the behavior of an ant species such as *Pogonomyrmex barbatus* that is not as effective at group retrieval to better understand the factors behind successful transport. To speed the growth of the transport group to a size that is sufficient to move a payload, we can incorporate the ant behavior of recruitment [26] into our model.

Another future objective is the implementation of the ant-like cooperative transport strategies on a multirobot testbed. Robot experiments are needed to assess the strategies under real-world conditions that are difficult to capture in a physics-based simulation environment, including accurate contact mechanics and the effects of realistic sensors and actuators. The ant transport simulation can be translated to a multirobot scenario by adapting the dynamic manipulation model to robotic transporters as in [36], where the model was validated using the robots in Fig. 1. Implementing the simulated control policies on these robots will require decentralized strategies for locating attachment points on an object, such as through a vision-based method; grasping these points firmly; agreeing on the target destination through a consensus algorithm if it is not preprogrammed; and navigating toward this location while avoiding obstacles and other robots. While ants can sidestep during transport, the robots are nonholonomic and so they cannot imitate these maneuvers, which must be taken into account in their motion control. The simulation and robot experiments can be used to study whether ant transport is optimal in some sense, such as minimizing the forces that individuals apply. ■

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