Natural-artificial hybrid swarm: Cyborg-insect group navigation in unknown obstructed soft terrain

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Navigating multi-robot systems in complex terrains has always been a challenging task. This is due to the inherent limitations of traditional robots in collision avoidance, adaptation to unknown environments, and sustained energy efficiency. In order to overcome these limitations, this research proposes a solution by integrating living insects with miniature electronic controllers to enable robotic-like programmable control, and proposing a novel control algorithm for swarming. Although these creatures, called cyborg insects, have

the ability to instinctively avoid collisions with neighbors and obstacles while adapting to complex terrains, there is a lack of literature on the control of multi-cyborg systems. This research gap is due to the difficulty in coordinating the movements of a cyborg system under the presence of insects' inherent individual variability in their reactions to control input. In response to this issue, we propose a novel swarm navigation algorithm addressing these challenges. The effectiveness of the algorithm is demonstrated through an experimental validation in which a cyborg swarm was successfully navigated through an unknown sandy field with obstacles and hills. This research contributes to the domain of swarm robotics and showcases the potential of integrating biological organisms with robotics and control theory to create more intelligent autonomous systems with real-world applications.

Introduction

The research on swarm navigation, referring to guiding a collective of agents to traverse an environment together, has captured increasing attention in recent years (*1–6*). By harnessing the collective intelligence of autonomous entities, swarm navigation not only facilitates efficient traversal of unexplored terrains (*7–9*) but also extends its utility to various sectors such as logistics (*10, 11*), disaster response (*12*), and agriculture (*13*). In logistics, swarm navigation optimizes route planning among multiple vehicles, enhancing transportation efficiency and reducing costs (*10, 11*). In disaster response, it enables coordinated efforts among robotic teams to support disaster monitoring and survivor searching (*12*). In agriculture, it supports precision farming techniques, monitoring crop health, and automating tasks to increase productivity and minimize environmental impact (*13*).

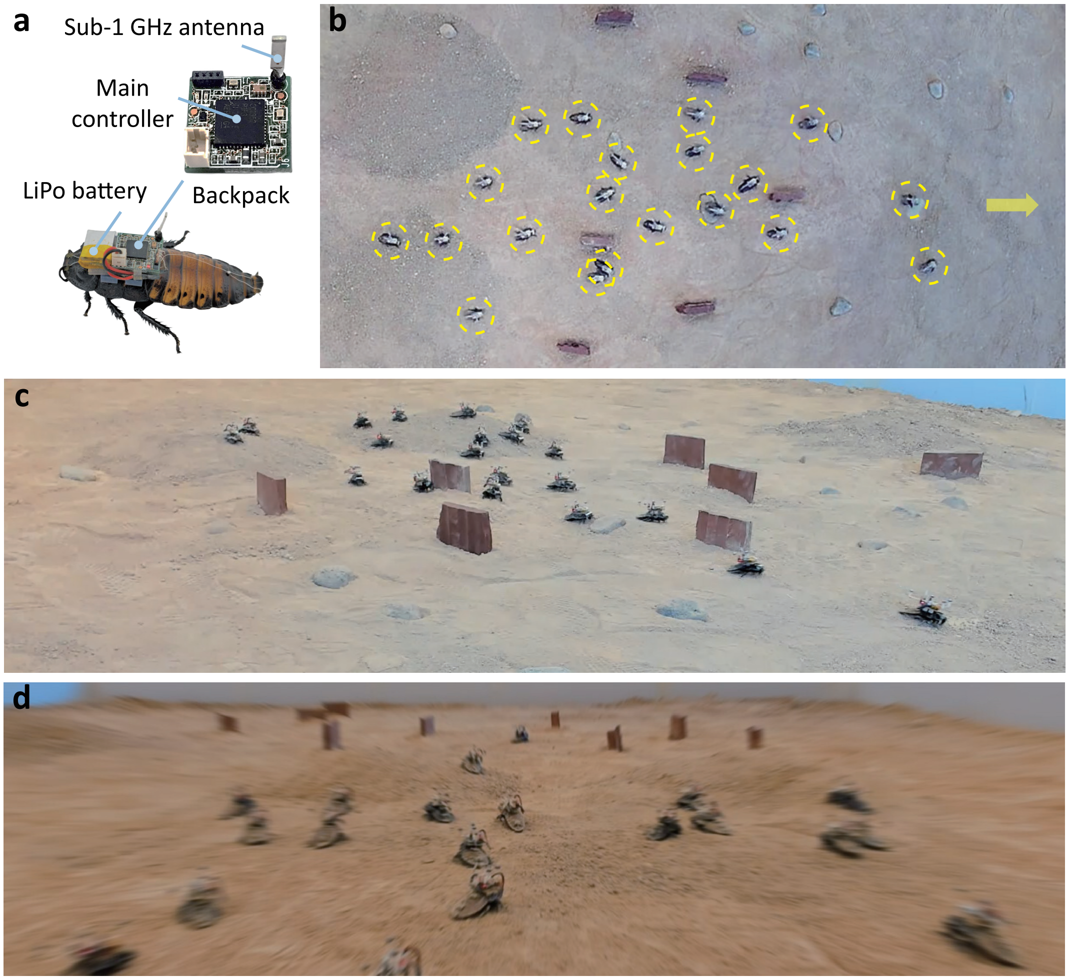

Figure 1: Overview of the cyborg swarm navigation. **a** A cyborg insect. In this work, the Madagascar hissing cockroach (Gromphadorhina portentosa) was chosen for the cyborg system. A backpack circuit board attached to the insect was designed to house the necessary systems, including the locomotion control system and wireless communication module. It was powered by a rechargeable LiPo battery. How to prepare a cyborg insect is detailed in the supplementary materials. **b** An illustration of cyborg swarm navigation (top view). A decentralized algorithm was proposed to navigate the cyborg swarm to a designated goal through a sandy area in the presence of hills and obstacles. All the cyborgs have no information about obstacles and hills in the field. **c** The side view and **d** the back view of a cyborg swarm. A comprehensive presentation of this work can be found in Movie S1.

However, using conventional robotic platforms such as UAVs and UGVs in swarm navigation has notable drawbacks, including their relatively large size and limited mobility. These drawbacks pose practical challenges, especially in constrained or crowded environments where spatial limitations impede effective task execution. In addition, their ability to operate in large terrains is directly constrained by the battery capacity, which limits endurance and overall efficiency.

This study introduces cyborg insects as a solution to the limitations of traditional robots in swarm navigation. Cyborg insects (Fig. 1a), which combine living insects with miniature electronic controllers, offer several advantages over conventional robots (*14–18*). One of the advantages is their energy efficiency. Unlike robots, which typically rely on power-consuming drive mechanisms like motors for movement, cyborgs leverage the natural mobility of insects, requiring less energy consumption (*16, 18*). Cyborgs also excel in adapting to complex terrains (*14, 15*). They can effortlessly maneuver around obstacles of various shapes and sizes and easily navigate through narrow spaces. Additionally, cyborgs are equipped with sophisticated sensory systems, enabling them to rapidly perceive and respond to their environment (*17*). They detect obstacles quickly and take decisive action to avoid or overcome obstacles thanks to their innate sensing mechanism.

Because of these fascinating features, research on cyborgs has recently gained increasing attention. Studies on cyborgs in (*19, 20*) have mainly demonstrated their functionality in obstacle-free environments. Works in (*21–23*) allow a single cyborg to navigate in rather complicated terrain by manually manipulating it along a preplanned path. In addition, the cyborg developed in (*18*) can navigate to predetermined destinations and autonomously traverse unknown terrain. However, despite the aforementioned achievements in single-cyborg control, to the best of our knowledge, the multi-cyborg navigation problem has never been addressed in the literature (an illustration of a cyborg swarm can be seen in Figs. 1b, 1c, and 1d).

A multi-agent system presents numerous advantages compared to a single-agent system, such as fault tolerance (*24, 25*), distributed problem-solving (*26, 27*), and applicability to large-scale problems (*28*). Furthermore, the multi-cyborg system offers unique benefits, particularly in terms of enhanced robustness and intelligence. Regarding robustness, the interactions among the cyborgs in a multi-cyborg system can improve their ability to recover from an overturn because a well-designed swarm control algorithm can allow overturned cyborgs to be surrounded by neighbors that provide support points and aid in their rapid recovery. Additionally, the swarm behavior of a multi-cyborg system contributes to its intelligence. For example, if a cyborg slows down in a potentially difficult area, other cyborgs can be implicitly instructed to navigate around it, effectively guiding the swarm to avoid obstacles. This cooperative behavior is similar to common human strategies, such as selecting shorter checkout lines in supermarkets for faster service. Furthermore, with appropriately designed swarm control algorithms, cyborgs that bypass the challenging zone can collectively assist the individuals trapped therein, resulting in the passage of the entire swarm.

Controlling multiple cyborg insects is challenging due to their inherent variability. Each insect may respond differently to the same stimulus voltage, complicating precise control compared to artificial machines. While managing a single cyborg may be feasible despite this variability, it becomes a critical issue for controlling a cyborg swarm. When neighboring cyborgs in a swarm are not precisely driven to their target locations, entanglements may occasionally occur among cyborgs in close proximity under electric stimulations at the moment (although they can autonomously avoid entanglements when not being stimulated, namely, under free motions). While adaptive or robust control methods (*29–31*) may address the entanglement problems caused by individual variability to some extent, their implementation requires complex control laws, which is not very practical for small, computationally limited cyborgs. Furthermore, a complicated control algorithm design contradicts our intention to exploit the inherent biological instincts of insects. This research proposed a control algorithm that addresses the aforementioned issues, and verified it under experiments.

Swarm navigation algorithm design

The proposed algorithm in this paper can navigate a swarm of cyborgs from the start to a predetermined goal in an unknown sandy terrain in the presence of obstacles and hills (Fig. 2a). The multi-cyborg system to be controlled is composed of a leader and several followers, with agents capable of basic directional steering and forward motion. Each agent can detect neighbors within a limited sensing range and distinguish the leader from the followers. Only the leader is given the position of the goal. The proposed algorithm consists of two main components: motion planning and trajectory tracking (Fig. 2b). The motion planning algorithm provides the desired positions of cyborgs for the next time step based on their local information. The trajectory tracking algorithm then receives this information and computes the corresponding amplitude and types of stimulation (left, right, or acceleration) to be applied to the insects.

Our motion planning algorithm was developed on the basis of the observed behavior of tourists who follow a tour leader. Specifically, the algorithm consists of the following two clear and simple rules. The first rule is the free motion (FM) rule, which grants followers the freedom to move when the leader is visible or when they remain close to the crowd. Otherwise, they adhere to the move-toward-crowd (MTC) rule, which guides followers toward the leader when visible and toward the direction of the crowd when not visible. Combining these rules, we propose the Tour Group Inspired (TGI) control algorithm. It can be applied to the multi-cyborg system: if the number of neighbors m_i within follower i's free range (i.e., a circular area around it whose radius is smaller than its sensing range) is less than a threshold M, follower i follows the MTC rule; otherwise, it makes free motions.

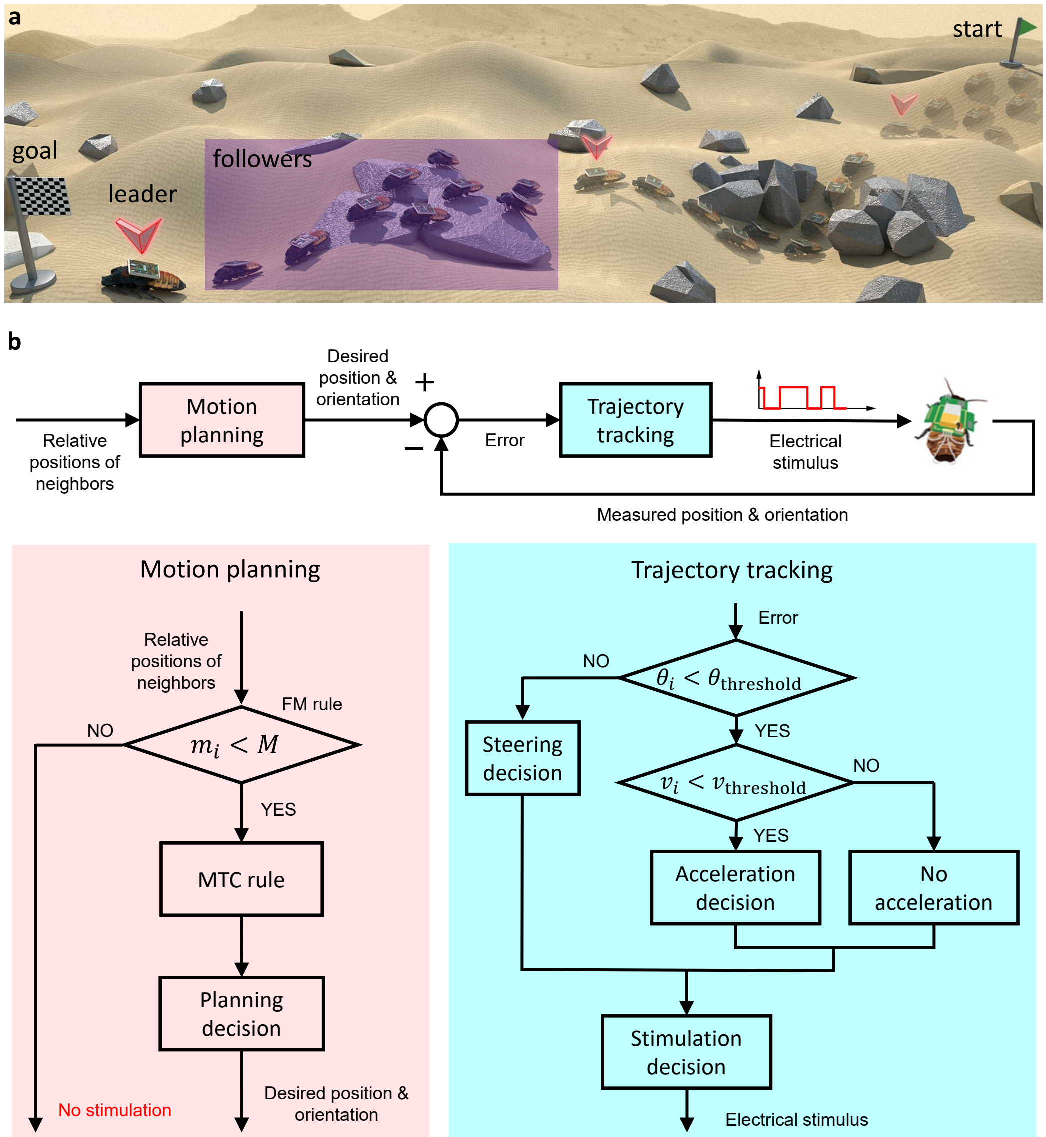

Figure 2: **a** Statement of the swarm navigation problem. **b** An illustration of the proposed control strategy. The control strategy consists of two parts: motion planning and trajectory tracking. The motion planning algorithm provides the desired positions of cyborgs for the next step based on their local information and passes it to the trajectory-tracking algorithm. The trajectory tracking algorithm computes the corresponding amplitude and types of stimulation (left, right, or acceleration) to be applied to the insects.

We then present the details of our design of the trajectory tracking algorithm. We note that two types of stimulation, steering (left or right) and acceleration, can be applied to the insects. Based on stimulation, the algorithm operates as follows. For each follower i, the algorithm first divides its free range into several sectors. Then, the algorithm selects an arbitrary cyborg from the target sector (the one with the most neighbors) as the target cyborg, and steer the follower toward it. If angle θ_i between the current moving direction of follower i and a line connecting itself with the target cyborg is less than a threshold $\theta_{\text{threshold}}$, steering is not applied, and the algorithm proceeds to the acceleration decision. The rule that governs the acceleration is designed as follows. No acceleration will be applied if follower i's speed v_i exceeds a certain threshold $v_{\text{threshold}}$. Otherwise, acceleration will be applied, and its magnitude is proportional to the distance between the follower and the target cyborg. This magnitude is bounded by the maximum voltage (2.5V) a cyborg can bear. Details of the control algorithm design are given in the supplementary materials.

Our TGI control algorithm capitalizes on the free motions of insects, potentially enhancing efficiency in obstacle and terrain negotiation. Additionally, the utilization of free motions decreases the frequency of electric stimulations on insects. Consequently, it reduces the likelihood of habituation of insects, saves the battery power of the backpack, and, in turn, prolongs the utilization of the cyborgs. Moreover, the FM rule in the TGI algorithm mitigates the impact of insects' individual variability on control performance. Specifically, the FM rule enables free motions of cyborgs in densely packed parts of the swarm, effectively averting entanglements and thereby bolstering the robustness of the multi-cyborg system.

Experimental verification of the proposed algorithm

The feasibility of the proposed swarm navigation algorithm is tested under real-world experiments in a proof-of-concept but challenging scenario. Ten trials of experiments were conducted to demonstrate the reproducibility of experiments.

The experiments used 20 cyborgs as the robot platform in a 3.5m by 3.5m sandy field with rocks and hills (Fig. S1c in the supplementary materials). Among the 20 cyborgs, there is one leader, and the other 19 are the followers. The leader knows the goal position, and the 19 followers only know their neighbors' relative positions. The followers can distinguish between the leader and the followers. All the cyborgs have no information about obstacles and hills in advance. Details of the experimental setup are given in the supplementary materials.

The proposed control strategy has been successfully implemented on the multi-cyborg system, effectively guiding the swarm to the designated goal area. To demonstrate the reproducibility of experiments, ten trials of experiments were conducted, and the corresponding results are summarized in Fig. 3. The trajectories of the cyborgs are presented in Fig. 3a, where the leader's path, the followers' trajectories, the positions where cyborgs were stimulated, and the final positions of all 20 cyborgs are presented with a yellow curve, blue curves, red circles, and black dots, respectively. Fig. 3c shows the corresponding top view of Exp 1. In Figs. 3d and 3e, snapshots capture different moments of Exp 1: the initial distribution of the 19 followers and placement of the leader (both front and back views) and the final state with all cyborgs reaching the goal area (front view). The results of Exp 2 to 10 are shown in Fig. 3b.

The degree of autonomy depicted in Fig. 4 illustrates the efficacy of the proposed algorithm in leveraging insects' instincts. The degree of autonomy is computed as the average ratio between the time without stimulation and the whole experimental period of all the followers. Thanks to the FM rule in the TGI algorithm, the electric stimulation was applied to insects only

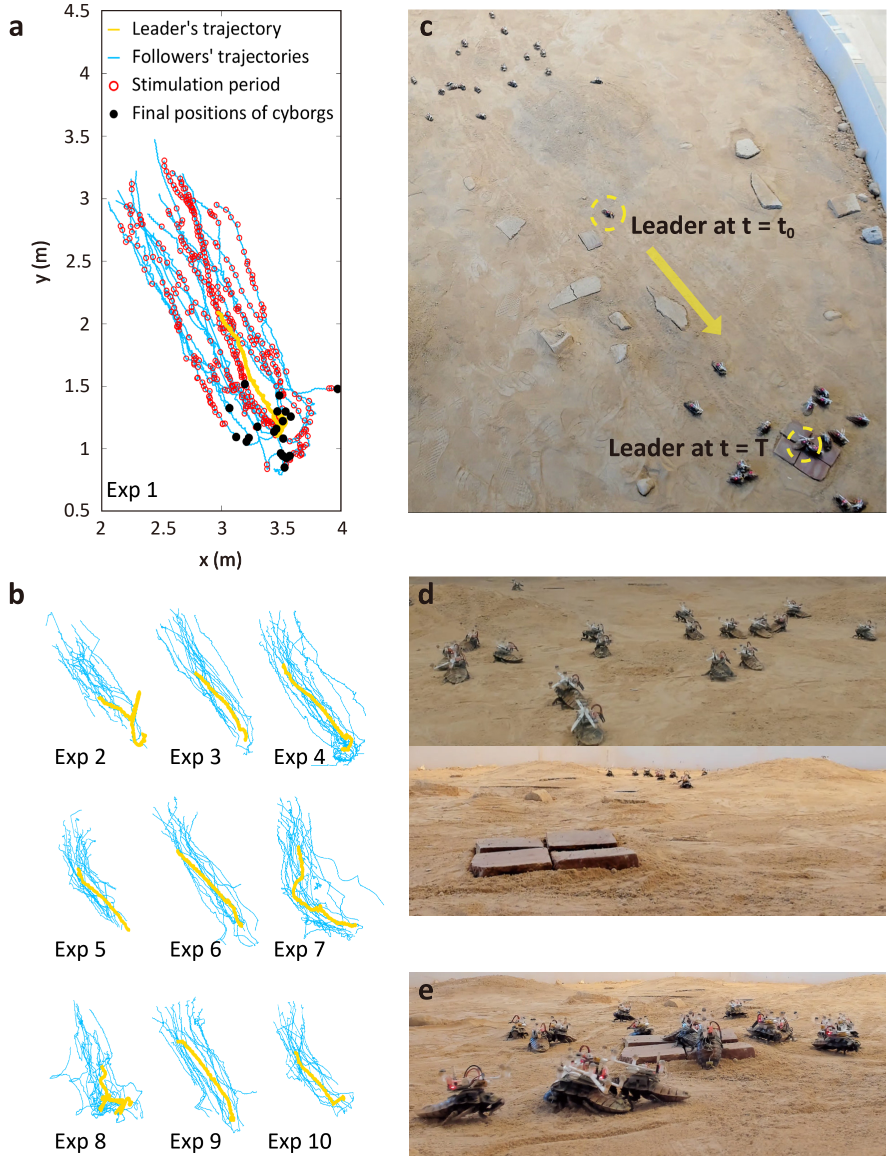

Figure 3: Swarm navigation experiments. **a** Path plot of Exp 1. The paths of 19 followers are depicted in blue and that of the leader is in yellow. When stimulations are applied to any of the followers, the red circle is displayed at the corresponding positions on the paths, and the black dots denote the final distribution of 20 cyborgs. **b** Path plots of Exp 2 to 10. **c** The top view of Exp 1. The yellow circle marks the leader. **d** Snapshots of cyborg swarm at the initial state $t = t_o$ of Exp 1 (front and back views). **e** Snapshots of the cyborg swarm at the final state $t = T$ (front view). The video of Exp 1 is Movie S2.

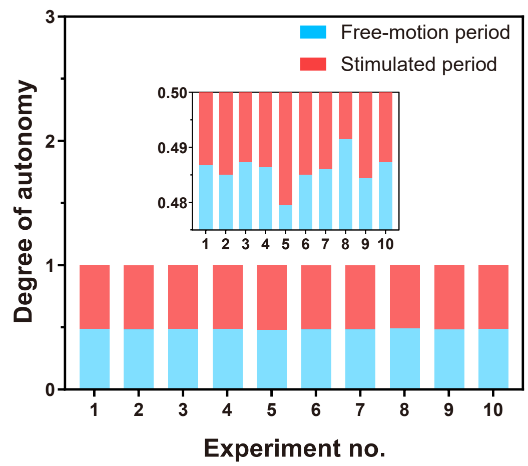

Figure 4: The degree of autonomy for 10 trials of experiments. In this study, we define the degree of autonomy for the multi-cyborg system as follows: for each experimental trial, we calculate the ratio a_i between the time without stimulation and the whole experimental period for each follower i. Then, the degree of autonomy of this trial is defined as the average $(a_1 + \cdots + a_N)/N$, where N denotes the number of followers. As shown in this figure, in all the trials, stimulations are applied to the followers during only half of the experimental period on average. This occurrence is attributed to the FM rule in the TGI algorithm, which decreases the frequency of electric stimulations on insects. Consequently, the FM rule mitigates the likelihood of habituations of insects, saves the battery power of the backpack, and in turn, prolongs the utilization of the cyborgs.

around half of the experimental period. Consequently, the FM rule mitigates the likelihood of habituation of insects, saves the battery power of the backpack, and in turn, prolongs the utilization of the swarm system.

Discussion

During the experiments, several other intriguing phenomena demonstrated the features of the proposed TGI control algorithm:

- The employment of free motions reduces entanglements among cyborgs, thus leading to a higher safety of the multi-cyborg system.
- The interactions among neighbors may facilitate a trapped cyborg to escape a difficult situation.
- Neighbors can help a cyborg recover from an overturn, which, in turn, enhances the robustness of a cyborg swarm.

These features are detailed as follows.

First, the TGI control algorithm improves the safety of the multi-cyborg system by reducing entanglement between cyborgs. Our experiments showed that cyborgs instinctively avoid collisions with neighbors during free movement. However, when two cyborgs approached each other too closely and the separation rule from the conventional BOIDS algorithm (*32*) was applied to stimulate the cyborgs to move away from each other, they failed to separate and instead became entangled. Entanglement can lead to undesirable results, such as damage to the cyborgs. This problem was often encountered with the conventional control based on the BOIDS algorithm when neighbors became too close. As shown in Fig. 5a, entanglement occurred frequently (up

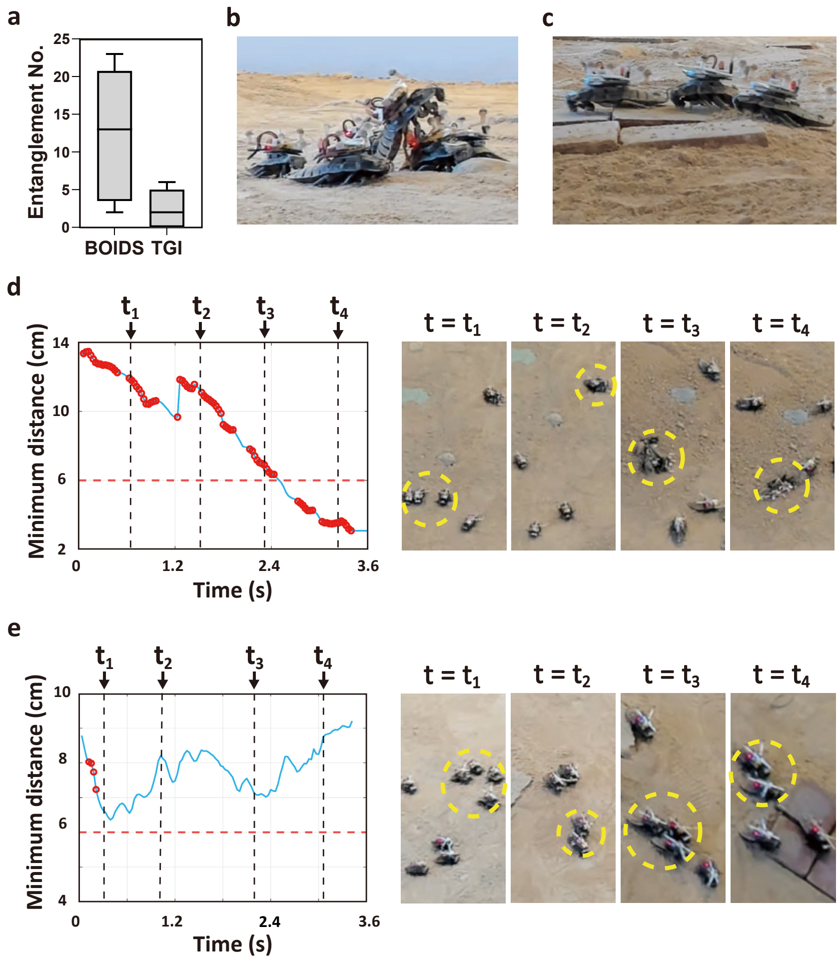

Figure 5: Entanglement frequency in experiments with the BOIDS and the proposed TGI algorithms. **a** The frequency of entanglements in 10 trials of experiments, respectively, under two control algorithms. **b** An illustration of entanglements: when parts of two or more cyborgs overlap with each other. **c** A group of close but non-entangling cyborgs. **d** The minimum distance among all pairs of cyborgs circled out in the figure and experimental snapshots in one trial of an experiment conducted with the BOIDS algorithm. Red points indicate instances where at least one of those cyborgs received electrical stimulation. The frequent stimulations on cyborgs that are too close to each other lead to entanglements (distance less than 6 cm). **e** One trial under the TGI control algorithm. When the distance between cyborgs is close, the TGI algorithm avoids stimulating them, allowing them to avoid entanglement instinctively. The snapshots reveal that cyborgs can move closely and parallel without entanglements. See Movie S3.

to 23 times) under the BOIDS algorithm. The feasibility of using free motion to prevent entanglement is demonstrated in Fig. 5b and Fig. 5c. When the cyborgs approached each other, the BOIDS method tried to separate them by applying intensive stimulation, which proved to be unsuccessful (Fig. 5d). Conversely, the proposed TGI control exploited the free motion of the cyborgs, taking advantage of their innate behaviors to avoid entanglement (Fig. 5e). Fig. 5a shows that the entanglement frequency for cyborgs under the TGI control algorithm is significantly lower than that under the BOIDS algorithm.

Second, the interactions among neighbors can help a trapped cyborg escape a difficult situation. As shown in Fig. 6, in an experiment, a cyborg's "Y" shape marker became wedged on the edge of an obstacle. Meanwhile, following the proposed control algorithm, other cyborgs were navigated around the cyborg, which indirectly let the swarm bypass the obstacle. Furthermore, it is noteworthy that, in line with the MTC rule of the proposed control algorithm, cyborgs bypassing challenging zones can assist trapped cyborgs, facilitating the passage of the entire swarm. As illustrated in Fig. 6, when the cyborg marked by a yellow circle initially became wedged on an obstacle, it remained unstimulated due to its proximity to the neighbors. However, when the neighbors were bypassing the stuck one ($t = t_2$), they started to "attract" it (stimulations were reapplied to the cyborg), pulling it away from the obstacle.

Third, neighbors can aid a cyborg in recovering from an overturn. In the presence of neighbors, the overturned cyborg can use neighbors as supporting points for more efficient uprighting. Fig. 7a illustrates three cases of self-attempted and neighbor-aided recovery from overturns. The discrepancy in recovery performance is particularly evident in Case 3, where a cyborg struggled for 26.5s before grasping a passing neighbor and then successfully recovered in only 4.5s. Snapshots of Cases 1 and 3, where cyborgs recovered with the help of neighbors, are provided in Figs. 7b and 7c, respectively. The proposed TGI control algorithm ensures the presence of neighbors around each cyborg and, in turn, enhances the robustness of the multi-cyborg system.

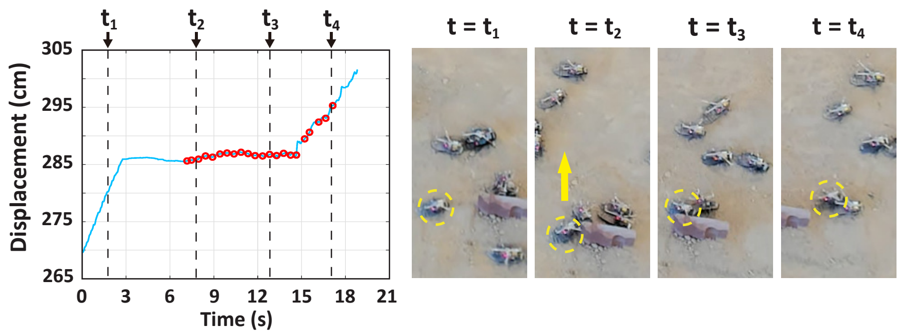

Figure 6: The process of a trapped cyborg being saved by neighbors. In experimental snapshots, the cyborg marked by a yellow circle is on the verge of getting stuck with an obstacle. The first snapshot shows that the target cyborg approached the obstacle. Naturally, there is a corresponding displacement change. The second snapshot signifies the moment when the cyborg encountered an obstacle, impeding its movement, and therefore, the displacement almost remained the same during this period. The surrounding cyborgs navigated around the trapped one and the obstacle. The third snapshot demonstrates that, through our algorithm, the trapped cyborg gradually overcame the obstacle with the "attractive force" from other cyborgs, and the displacement started changing again. The red dots in the displacement plot represent electrical stimulations applied to the cyborgs according to our algorithm. The last snapshot signifies the recovery of the initially trapped cyborg's movement: the cyborg detached from the obstacle and resumed its motion toward the target. See Movie S4.

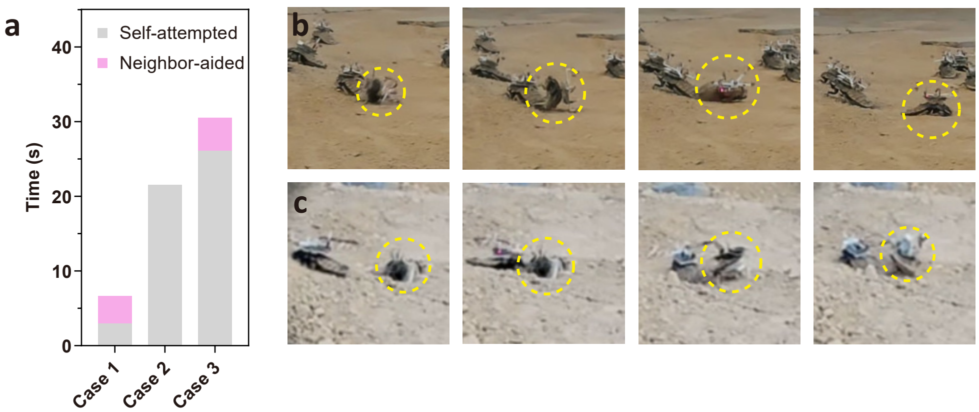

Figure 7: Recovery from an overturn. **a** Time for a cyborg to recover from an overturn for three trials of experiments. The grey bar denotes the time a cyborg attempted to recover by itself. The bar's bottom and top indicate the start and ending times. Similarly, the purple bar denotes the time taken with help from a neighbor. In Cases 1 and 3, the cyborg in the overturned state first attempted and failed to recover by itself for a while, then successfully recovered by grabbing a passing neighbor. **b** The snapshots of the recovery process of Case 1: the overturned cyborg grabbed an approaching neighbor and, with its help, successfully recovered. **c** The snapshots of the recovery process of Case 3. See Movie S5.

In summary, this paper studied a swarm navigation problem for a multi-cyborg system. A control strategy has been proposed to tackle this problem and verified under experiments. The proposed control algorithm offers several notable advantages. Firstly, it efficiently utilizes the instincts of insects, exploiting their inherent adaptability to various environments. Additionally, by leveraging these instincts, the algorithm reduces the frequency of electric stimulations, consequently extending the operational duration of the system. Moreover, the decentralized nature of the control algorithm ensures its scalability to a larger swarm, as each cyborg makes decisions based on only local information.

Note that although the control algorithm proposed in this work is theoretically fully decentralized, the cyborgs in our experiments were provided data from a centralized motion capture system. We are considering more advanced positioning systems to address this issue in future work. A feasible solution is using a micro-nano inertial measurement unit (i.e., the Honeywell MV 60 high-precision micrometer) and radio frequency identification (RFID) technology for localization. The advantages of this solution are as follows: firstly, the micro-nano inertial navigation unit can match the body size of cockroaches and provide centimeter-level positioning accuracy within a certain period; secondly, to address the error accumulation property of accelerometers, RFID modules can be deployed around the site which update the location information of cyborgs at intervals, and thus zero out the accumulated errors of the accelerometers. This solution can be a promising direction for the practical utilization of the proposed control strategy.

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Supplementary materials

Materials and methods

Fig. S1

Movies S1 to S5

References (33, 34)