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RAPID COMMUNICATION

Bio-inspired environmental adaptability of swarm active matter

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How biologically active matters survive adaptively in complex and changeable environments is a common concern of scientists. Genetics, evolution and natural selection are vital factors in the process of biological evolution and are also the key to survival in harsh environments. However, it is challenging to intuitively and accurately reproduce such long-term adaptive survival processes in the laboratory. Although simulation experiments are intuitive and efficient, they lack fidelity. Therefore, we propose to use swarm robots to study the adaptive process of active matter swarms in complex and changeable environments. Based on a self-built virtual environmental platform and a robot swarm that can interact with the environment, we introduce the concept of genes into the robot system, giving each robot unique digital genes, and design robot breeding methods and rules for gene mutations. Our previous work [*Proc. Natl. Acad. Sci. USA* **119** e2120019119 (2022)] has demonstrated the effectiveness of this system. In this work, by analyzing the relationship between the genetic traits of the population and the characteristics of environmental resources, and comparing different experimental conditions, we verified in both robot experiments and corresponding simulation experiments that agents with genetic inheritance can survive for a long time under the action of natural selection in periodically changing environments. We also confirmed that in the robot system, both breeding and mutation are essential factors. These findings can help answer the practical scientific question of how individuals and swarms can successfully adapt to complex, dynamic, and unpredictable actual environments.

Keywords: self-adaptability, active matter, robot swarm, dynamics of evolution

PACS: 87.23.–n, 87.23.Kg, 87.85.St **DOI:** 10.1088/1674-1056/acd688

1. Introduction

The issue of survival is the most important and challenging problem that biologically active matters face.[1–3] Each biologically active matter must master the skill of surviving in complex and ever-changing natural environments. Various species in nature, whether they are flocks of birds flying in the air, herds of sheep running on the ground,[4,5] or schools of fish swimming in water,[6] have developed significantly different survival strategies over the course of billions of years of evolution. But from a microscopic point of view, they all follow the theory of evolution. Genetics, evolution, and natural selection play a decisive role.[7,8] However, since genetic evolution is a long-term behavior on the time scale, it is nearly impossible to completely replicate this evolutionary characteristic of life in artificially active matter systems.[9,10] In addition, common artificial active matter systems lack accurate environmental quantification methods, making it difficult to precisely control and quantify the complex environments in active matter experiments.[11] The main traditional solution is to use computer to simulate the interactions between the biological population and the environment, compressing the time scale of tens of thousands of years into an acceptable time range. Simulation is very efficient, and its results are often very intuitive.[12,13] It can visually represent the interactions and impacts between agents and the environment, making it easy to study quantitatively. However, there is an obvious drawback to simulation experiments, which is the lack of fidelity.[14] The simulation model is often too idealistic to reproduce the various environmental noises and small events in the real world that affect the macroscopic results.[15–17]

Robot swarm, as a special type of artificial dry active matter, has significant advantages and features in the research of active matter.[18–21] Micro-robots controlled by digital chips have high controllability and can define their own properties through programming.[22,23] Compared to traditional active particles, using robot swarms to study active matter has greater flexibility.[1,24] In recent years, many impressive successful research cases have been reported on the interaction between agents[25,26] and the interaction between agents and environment.[27–29] Using robot swarms to study active matter not only allows customization of individual properties but also enables the complete storage of detailed data from experiments for quantitative analysis.[30,31] Moreover, compared

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with pure simulation experiments, the robot swarm has more realistic noise and heterogeneity, which are very important factors in the behavior of active swarms.[32]

Therefore, we designed and manufactured a batch of interacting robot swarms, and also constructed a virtual environment platform based on LED light boards. On this platform, robot swarms can interact with the environment, meaning that individuals can not only perceive the environment but also actively modify it. All interactions among individuals and interactions between individuals and the environment can be recorded for quantitative analysis. Based on the system's properties, we introduced the core concept of biological evolution into the experimental system, giving robots special digital genes, special reproduction process, gene mutation rules, and combined with a dynamic evolutionary resource landscape that mimics natural environments.

In our previous work,[33] we found that such a system will exhibit different properties in different environments, and in complex environments, robots can also survive adaptively. However, there is still a lack of more complete evidence support and conditional verification in terms of why robots can survive in a changing environment and whether groups can survive for a longer period of time. Therefore, in this work, we set up experiments under four different conditions to confirm that in the evolutionary rules of this robot system, the respective roles of breeding and mutation are indispensable. Moreover, we verified the evidence of adaptability of robots to the environment from the Fourier power spectrum of the population survival curve and the correlation between the proportion curve of gene traits and the environmental resource curves. In addition, we also used simulation experiments to further confirm the effectiveness of this system, which is also lacking in previous work. The work in this paper makes robot swarms completer and more reliable as experimental models of evolving systems.

2. Methods

2.1. Design of the robot–environment interaction system

In nature, the environment is usually complex, dynamic, and multi-layered. A localized biological system not only has a highly uneven distribution of spatial resources, but also experiences temporal fluctuations in the environment.[34] In addition, different animals with different diets have varying resource requirements, and their resources often overlap with each other, resulting in both competition and cooperation within the biological system. The behavior of individuals and groups within the entire system is extremely dynamic, complex, and difficult to predict accurately. Therefore, the environmental platform we created must simultaneously satisfy the characteristics of multi-layered environments with complexity, dynamism, and quantifiability. To enable interaction among individual robots and between individuals and the environment, individuals must have sensors that can perceive other individuals and the environment, as well as methods to actively change the environment.

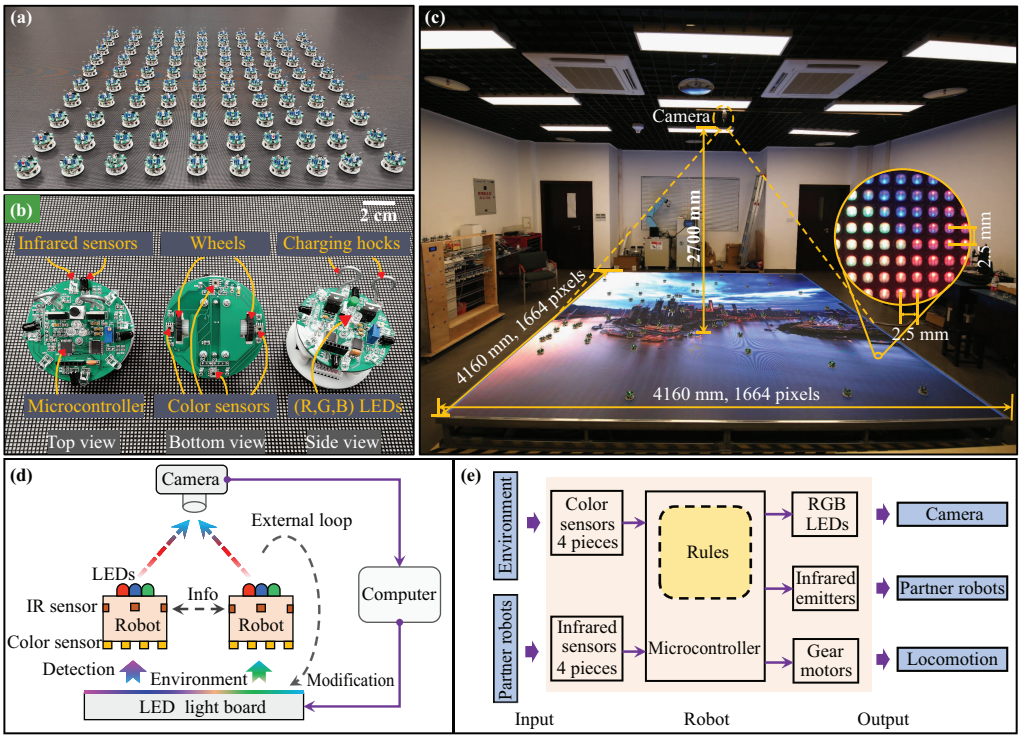


Fig. 1. Robots and the interactive environment. (a) Swarm of 100 robots. (b) Robot movement is controlled individually by two motors. A robot base has four color sensors for detection of the LED light board. Each top has three LED lights that exhibit their status through variable colors of light (red, green and blue). The robots also have 4 pairs of infrared emitters and receivers to sense the surrounding neighbors. Battery charging is realized through the hooks. (c) The giant LED light board could display the dynamic environment for robots. The upper camera is for real-time monitoring and tracking robots. (d) The process of the interaction between the robots and the two-way interaction between the robot and the environment through the camera system. (e) The way a robot interacts with the surroundings through sensors and actuators.

Figure 1 shows the swarm robots and environmental platform used in this work. As shown in Fig. 1(b), each robot has an independent microcontroller that stores data and makes individual decisions based on preset rules in response to the environment. The robots have four pairs of infrared emitters and receivers for exchanging information with neighbors, and two gear motors that can independently drive the robot's movement, allowing the individual to turn around or move straight. At the bottom of the robot, there are four color sensors that help the robot to independently recognize the gradient direction of the resource field around itself by detecting the color information at four positions. The red, green, and blue LED lights on the top of the robot can convey the individual's interaction with the environment to the camera above the platform through color combinations. After being processed by the camera system, the individual's modification of the environment can be updated in real time on the screen.

The dynamic evolution of resource landscape is presented using a giant LED light board, as shown in Fig. 1(c). The size of the environmental platform is 4.16 m×4.16 m, with a pixel resolution of 1664 pixels×1664 pixels. The distance between the LED beads is 2.5 mm, and each bead can independently display red, green, blue, or mixed colors of light. With a self-developed control program, the color and brightness of each bead can be accurately controlled. Therefore, the platform can display extremely rich and accurate environmental information. The cartoon in Fig. 1(d) depicts the mutual perception process between robot individuals and their environment. The robot detects resource distribution via its color sensor and adjusts its movement accordingly. Simultaneously, the camera captures the robot's position and status via the LED lights on the top of the robot. Rapid processing by the computer enables real-time updates of environmental changes to the robot's location, creating a two-way interaction mechanism between the individual and the environment. When two robots' infrared sensors align, they can exchange information and interact with each other. Figure 1(e) briefly shows the way by which a robot interacts with the outside world.

2.2. Definition of biological evolution characteristics of robots

The main challenge of incorporating evolutionary characteristics from biological systems into robotic systems is that robots are not real creatures and can only abstractly represent genes, traits, and reproductive features through specific rules. Therefore, one of the key points of this work is to design a special biological characteristic mapping relationship from biological individuals to robots, so as to construct an experimental system of reproductive evolution based on the swarm robotic active matters.

In this work, the three different colors of red, green, and blue represent different types of resources, and the brightness of the light indicates the abundance or poverty of resources. When the robot moves in the resource landscape, it will detect the strength of various resources in the environment and then choose the direction of the largest resource that suits it. Figure 2(a) shows how a robot detects the resource intensity in an environment with multiple overlapping colors. Four color sensors can independently detect the red, green, and blue components in mixed color light, allowing for the calculation of resource gradients.

Corresponding to the genetic properties of biological individuals, each robot has a set of digital genomes consisting of three pairs of alleles, as shown in Fig. 2(b). Each digital gene consists of 8 binary digits, with the first digit determining the dominance of the gene, where '1' is dominant and '0' is recessive. The other seven bits determine the individual's sensitivity to resources. Different genes lead to different responses of the individual to the environment, as shown in Fig. 2(c). If a robot has the dominant red trait, i.e., its genotype is RR or Rr, then the robot will be sensitive to red light, and can consume red resource. If all three pairs of genes of the robot are dominant, the robot will be able to consume any color resource. If all three pairs of genes are recessive, the robot will not be able to consume any color resource. Robots with different dominant traits consume different amounts of resources, and the more dominant traits they have, the more resources they consume, as shown in Fig. 2(d). The more resources robots consume, the faster they move, but it becomes easier for the resources to become depleted. Therefore, only when the genes and traits of the robot match the type and amount of environmental resources can the individual survive for a long time.[35]

Figure 2(e) shows the relationship between the robot mutation rate and the resource intensity. In short, when the environment is less suitable for the individual to survive, the individual's survival pressure will increase, and the possibility of gene mutation will be higher.[36] The mutation is the same for each bit of genes, meaning that mutations can occur at any gene bit. Therefore, when a mutation occurs at the first bit of a digital gene, the dominance of that gene will be changed. As shown in Fig. 2(f), different types of resource intensity will exert different survival pressures on individuals with accordingly traits. For example, if an individual with only red dominant trait is in an environment with only green resources, it will face significant survival pressure. Shortages of resources of different colors will also generate corresponding pressures on different genes of the robot. That is, an individual with only red dominant genes will have a lower mutation probability of the red genes in a red resource environment, while in a green resource environment, the mutation rate of the red genes will be higher.

Since robots do not have the ability to directly reproduce new robots, it is impossible to produce a new robot with re-

combinant genes through the mating of two robots. Therefore, it is necessary to be flexible in the handling of the rule of reproduction. In our experiment, using dead robots as proxies for new reproductive robots is an important setting. As shown in Fig. 2(g), when a robot is in an unsuitable environment for a long time, and no suitable genes mutated, it will "die". Dead robots lose all their genes and mobility, becoming an inert shell that does not consume environmental resources anymore. Dead robots do not lose power, and their sensors continue to work. When the first surviving robot meets it, the surviving robot will randomly copy half of its genome to the inert shell. When the second robot contacts this shell, it will also randomly copy half of its genome to the dead robot. In this way, the inert shell will obtain the complete genomes and "rebirth" with the genetic characteristics of the two parent robots that contact with it. The robot's breeding rules also follow Mendelian inheritance as shown in Fig. 2(h). Therefore, the offspring has the genetic traits of both parents. Through this process, the robot population can continue to survive, and the genes can be spread within the population.

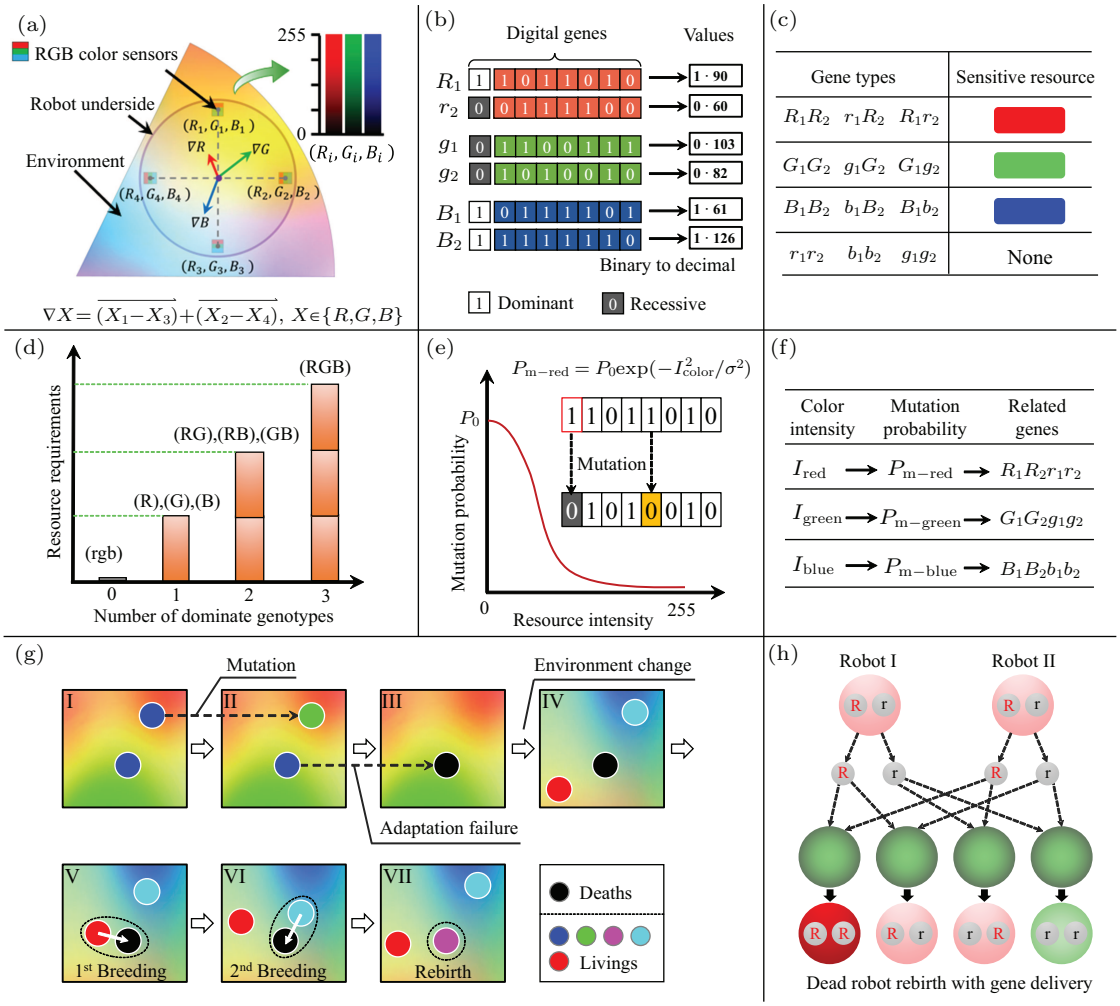


Fig. 2. The definitions of evolution characteristics of robots. (a) The robot can detect three types of resource distribution gradients in the environmental resource landscape var four color sensors at the bottom. (b) The diploid organization of each robot's genotype, two digital genes for each color. The first binary bit determines whether the gene is dominant or recessive. (c) Different traits consume different types of resources, and the effects of the three traits can be superimposed. (d) The more dominant traits, the greater the amount of resources consumed by the individual. (e) Mutation is internally set in each robot, and the mutation rates increase with lower levels of resources. Mutations have equal probability for each bit of the gene. (f) Resource shortages of different colors will act on their corresponding genes, resulting in different survival pressures. (g) Mutation, death and rebirth process of the robots in dynamic resource landscape. The dead robot is activated respectively by two living agents via gene delivery. (h) Diploid recombination of a dead robot from two successive live robot mattings.

Thus, we have fully defined the digital genomes composition of the robot, the mutation characteristics of genes in harsh environments, the death of individuals who are unsuited to the environment, and the unique reproductive rules among robot populations. Thereby we establish a set of new swarm robot active matter as an experimental model for agents to adapt to the environment through evolution.

2.3. Interaction mechanism between individual and environment

The speed and direction of a robot depend on both the state of the local environment resource landscape and the regulation of its own genes. Set the color measurement values of

the four color sensors on the robot's front, right, back, and left be (R'_1, G'_1, B'_1), (R'_2, G'_2, B'_2), (R'_3, G'_3, B'_3), and (R'_4, G'_4, B'_4), respectively. Considering that the color value range on the screen is 0–255, the normalized color gradients ∇I_{red}, ∇I_{green}, ∇I_{blue} are

$$\nabla I_{\text{red}} = \frac{\overrightarrow{(R'_1 - R'_3)} + \overrightarrow{(R'_2 - R'_4)}}{\sqrt{255^2 + 255^2}}, \tag{1}$$

$$\nabla I_{\text{green}} = \frac{\overrightarrow{(G'_1 - G'_3)} + \overrightarrow{(G'_2 - G'_4)}}{\sqrt{255^2 + 255^2}}, \tag{2}$$

$$\nabla I_{\text{blue}} = \frac{\overrightarrow{(B'_1 - B'_3)} + \overrightarrow{(B'_2 - B'_4)}}{\sqrt{255^2 + 255^2}}. \tag{3}$$

Set the six digital genes inside the robot to be R_1, R_2, G_1, G_2, B_1, and B_2 respectively. The first bit is the dominant or recessive 'flag' and the rest 7 bits are the 'values' which influence the sensitivity to the resource. The 7-bit values are between '0000000' and '1111111', which translate to decimal values between 0 and 127. Considering that only the traits determined by the dominant genes are sensitive to environmental resources, the normalized regulation coefficients of genes for speed R_{gene}, G_{gene}, and B_{gene} are

$$R_{\text{gene}} = \frac{R_1^{\text{flag}} \cdot R_1^{\text{value}} + R_2^{\text{flag}} \cdot R_2^{\text{value}}}{254}, \tag{4}$$

$$G_{\text{gene}} = \frac{G_1^{\text{flag}} \cdot G_1^{\text{value}} + G_2^{\text{flag}} \cdot G_2^{\text{value}}}{254}, \tag{5}$$

$$B_{\text{gene}} = \frac{B_1^{\text{flag}} \cdot B_1^{\text{value}} + B_2^{\text{flag}} \cdot B_2^{\text{value}}}{254}. \tag{6}$$

Since the robot's motor speed control method is pulse width modulation (PWM), with a maximum value of 255, when PWM is 255, the robot's speed reaches its maximum. Therefore, the actual speed of the robot is

$$\begin{aligned} \boldsymbol{V} \;=\; & 255 \cdot \frac{1}{3} \cdot (R_{\text{gene}} \cdot \nabla I_{\text{red}} + G_{\text{gene}} \cdot \nabla I_{\text{green}} \\ & + B_{\text{gene}} \cdot \nabla I_{\text{blue}}). \end{aligned} \tag{7}$$

Robots with different types of dominant traits consume resources of different types in proportion to the resource density of their environment. If a robot consumes resources in a range of R around its position (x_0, y_0), the distribution of resource consumption $S_{(x,y)}$ on each point inside the circular area centered at (x_0, y_0) and with a radius of R follows

$$S_{x,y} = C \cdot \mathrm{e}^{-\frac{D^2}{2\sigma^2}}, \tag{8}$$

where

$$D = \sqrt{(x - x_0)^2 + (y - y_0)^2}. \tag{9}$$

Let C denote the consumption rate of a dominant trait. For a robot with n dominant traits, the consumption rates of different types of resources, denoted as C_{red}, C_{green}, and C_{blue}, at a location with environmental resource densities (I_R, I_G, I_B) are given by

$$C_{\text{red}} = n \cdot C \cdot \frac{I_R}{I_R + I_G + I_B}, \tag{10}$$

$$C_{\text{green}} = n \cdot C \cdot \frac{I_G}{I_R + I_G + I_B}, \tag{11}$$

$$C_{\text{blue}} = n \cdot C \cdot \frac{I_B}{I_R + I_G + I_B}. \tag{12}$$

The total consumption rate of all robots is summed up to form a consumption matrix P_{shadow}, which has the same size as the background image matrix P_{ini}. The updated background image matrix P_{BG} is the difference between the initial background image matrix and the consumption matrix P_{shadow}. The computer updates the real-time image P_{BG} on the LED light board. The consumed resources will gradually recover, and the next moment's background image matrix P'_{ini} satisfies

$$P'_{\text{ini}} = P_{\text{ini}} - P_{\text{shadow}} \cdot \mathrm{e}^{-\frac{1}{\tau}}, \tag{13}$$

where τ determines the speed of environmental recovery, which is a fixed value in the experiment.

Therefore, every step of the robot's movement is determined by the distribution of resources in the environment as well as its own genetic characteristics. The environment has a slow recovery rate while being consumed by robot groups, and the environmental information is updated in real time through the LED platform.

2.4. Experiment settings

Robots with different traits consume different resources in the environment, and these traits are determined by their internal genes. Therefore, the behavior of robots on the environmental platform is essentially influenced by their internal genes. In these experiments, we set the environment as a circular area of fixed area, and 50 robots were randomly placed in the environment. Among them, 25 alive robots had random initial genes and can move, while the other 25 robots were in a dormant (dead) state, stationary in the environment, unable to move, and only the infrared sensor was operational. The environmental resources were composed of red, green, and blue components, and the three environmental color components were driven by sine functions, as shown in the top of Fig. 3(d). The sine functions driving these three environmental components have a phase difference of $2\pi/3$, which causes the environment to have one or two main colors at different times, and they alternate with each other over time. A complete environmental cycle is shown in Fig. 3(a). At the beginning of the experiment, the environment mainly consisted of red resources. Then, the green resource gradually increased, making the environment orange. When the red resources decreased to a low value and the blue resources were not yet strong, the environment mainly showed green. Later, the blue gradually became dominant, making the environment gradually blue, and finally,

the red resources slowly increased, making the environment gradually red again. Throughout the entire process, red, green, and blue alternated as the dominant colors.

In such a periodically changing environment, if the robot's genes do not change, the robot will soon die due to its inability to adapt to the environment. For example, a robot with only red dominant gene can only consume red resources, so at the beginning of the experiment, the robot can survive. However, as the red resource of the environment gradually decreases, the robot will die because it cannot obtain enough resources. In order to explore whether genetic mutations and the breeding function of the population are essential elements for the robot population to adapt to dynamically changing environments, we set up four different experiments to observe the adaptability of robot populations to the environment:

(a) Robots only have a complete genetic system, but no breeding or gene mutation characteristics.

(b) Robots have mutation characteristics, but there is no breeding ability between populations.

(c) Robots have the breeding ability of the population, but there are no gene mutation characteristics.

(d) Robots have a complete genetic system, and both the breeding function and gene mutation characteristics are normal.

The four conditions correspond to the extreme situations of population crises and states that different biological groups may face in nature. Due to the limitations of robot experiments, such as the duration of the experiment being restricted by battery and the possibility of mechanical or electronic errors, we also developed a corresponding simulation program based on the experimental setup described above. In the simulation experiment, the parameters are kept as consistent as possible with those of the real experiment. However, it should be pointed out that the simulation program cannot fully cover all the parameters of the real experiment, especially the complex actual interactions and collision between robots that cannot be completely reproduced by the simulation program. Therefore, the simulation experiment can only include the characteristics of the robots and the environment as much as possible and demonstrate whether the survival results of the group under long-term experimentation are consistent with those of the robot experiment.

3. Results and discussion

Figure 3(a) shows the resource landscape and robot distribution over time in the robot experiment. The environment gradually evolves from dominant red resources to dominant green resources, then to dominant blue resources, and finally returns to dominant red resources. Individuals in such a dynamically changing resource landscape experience constantly changing survival pressures over time. Therefore, populations under different conditions will exhibit distinguishing adaptive survival behaviors. Robots with different types of traits in the environment will consume different types of resources, so the flat resource environment will appear as shadows due to the resource consumption of individuals. When a robot perceives this shadow gradient, it moves in a more resource-dense direction. The swarm thus forms a dynamic cluster behavior. For robots whose genetic traits do not match environmental resources, they can only stay still because there are no suitable resources to consume. Their adaptation pressure increases sharply, and therefore probability of internal genetic mutations increases. When a robot's genetic traits change due to mutations, the change of the color of the LED indicator on the top of the robot is observed, and then the type of environmental resources it consumes also changes. Robot swarms with various characteristics will show different group survival results in the same environment. The results of the experiments under four conditions are described in detail below.

(a) When all the individuals in the group have neither the ability of gene mutation nor the ability of breeding, that is, the genes of the robot will not change, and the population cannot reproduce offspring. At the beginning of the experiment, the environment mainly had red resources. Most of the 25 individuals who initially had the random gene died quickly due to lack of the red dominant gene. The remaining robots survived by consuming red resources. As the experiment progressed, the group gradually died due to the depletion of red resources in the environment. Without the ability to breed and mutate, the entire group eventually became extinct in this periodic environment. The red line with triangle marks in Fig. 3(b) illustrates the rapid extinction process of this type of group.

(b) When robots have the ability to mutate their genes but cannot breed, they can survive longer in an unsuitable environment due to the emergence of appropriate genes caused by gene mutations. However, because the group cannot reproduce, and gene mutations are random, the number of robots in this group will only continue to decrease gradually as the experiment progresses and will eventually become extinct. The blue line with square marks in Fig. 3(b) illustrates the slow extinction process of this type of group.

(c) When robots cannot mutate their genes but have the ability to breed, they can activate dead robots through gene delivery. In this case, although robots could reproduce offspring, the efficiency of reproduction is too low. Therefore, when the environment becomes unfavorable, depending solely on reproducing offspring to produce new gene combinations is not enough to resist environmental changes, and the population will quickly become extinct. The magenta line with star marks in Fig. 3(b) illustrates this process.

(d) When the robot has both the ability of gene mutation and the ability to reproduce, the robot could adapt to the en-

vironment through gene mutation, and the ability to transfer genes suitable for the environment to new individuals through breeding process. In this case, some robots survived due to the favorable genes mutations when encountering harsh environments, and these individuals can also reactivate dead individuals through reproduction to become brand new individuals. These new individuals inherit genes adapted to the environment from their parents and are therefore more likely to survive. Thus, the number of populations is constantly fluctuating with changes in resources, but the group can continue to survive. The green line in Fig. 3(b) shows the dynamic change process of the population.

Based on the four comparative experiments described above, we have found that for robot systems that need to adapt to dynamically changing environments, both mutation and breeding are essential characteristics that cannot be missing. Gene mutations can help robot populations accumulate genes that are favorable for survival in new environments, while breeding ability ensures that the population is constantly replenished with new individuals that can adapt to the new environment. The absence of either of these elements will result in the gradual extinction of the robot population in a dynamically changing environment.

In order to more clearly compare population survival curves under different conditions, only typical experimental curves are shown in Fig. 3(b). Multiple experiments have verified that a population with mutation and reproductive abilities can indeed survive for a long time in such a resource-periodic environment, as shown in Fig. 3(c), the survival curves of the four experiments are shown in a scatter plot, with their mean shown in dark green. Fourier power analysis of the population survival curve reveals that the peak at 1440 timesteps period is equal to the peak period of the resource, see the inset illustration in Fig. 3(c) and the top of Fig. 3(d). This indicates that when any resource reaches its peak intensity, it is the local peak of population increase. This further confirms the adaptability of the population to the periodic resource environment.

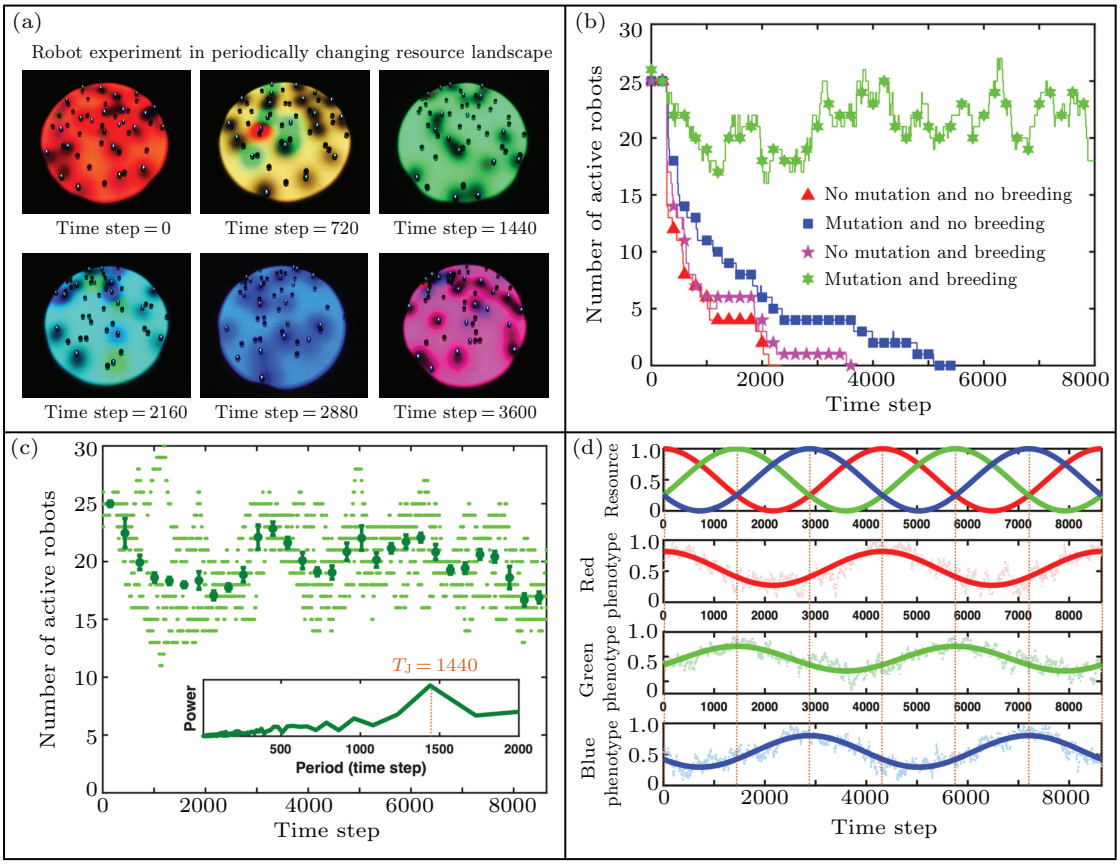


Fig. 3. Robot experiments in periodically changing resource landscape. (a) The color of the periodic resource landscape changes over time with a fixed radius. At 720 timesteps, the landscape is a superposition of green and red. A robot with a green dominant trait consumes green resources in the environment leaving red shaded areas. The white robots with three dominant traits will consume any kind of resource, leaving a dark shadow. (b) Robot survival curves for 4 different scenarios in the dynamic landscape. Red curve: no mutations, no breeding. Blue curve: mutations only. Magenta curve: breeding only. Green curve: robots could mutate and breed. The markers on the curve are only partial data points. (c) Survival curves of multiple experiments for mutations and breeding condition. The survival curves of the four experiments are shown in a scatter plot, with their mean shown in dark green. Fourier power analysis of the averaged survival curve is shown in the inset illustration. (d) Sinusoidal drive curves of the three-resource landscape fit well with the observed population fraction of dominant genes amongst the survival robot population. The semi-transparent curves represent the proportions of robots with different traits in the total surviving robots, and the solid lines are their fitting curves. The vertical dotted lines represent the corresponding relationship between the peak value of different dominant traits and the peak value of the corresponding color resources.

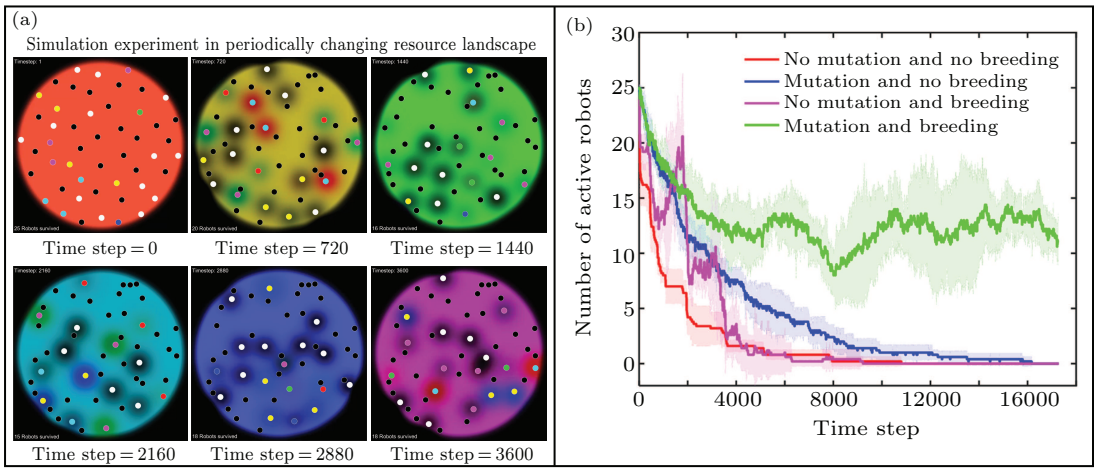


Fig. 4. Simulation experiments in periodically changing resource landscape. (a) Robot swarm states and resource landscapes during the simulation experiment. Robots with different dominant traits leave different shadows after consuming resources. (b) The simulation experiments show the same survival curve relationship as the robot experiments for four different scenarios. Areas of semi-transparent color represent the standard deviation of the experiments.

Because the experimental system can record complete data throughout the entire experiment, we can further analyze the results from the perspective of genetics and traits. Figure 3(d) shows the temporal distribution of the proportions of three different dominant traits in relation to each environmental component in surviving robots. At the top are the curves of different resource intensities during the experiment. The semi-transparent curves in the following three sets of figures represent the proportions of robots with red dominant traits, green dominant traits and blue dominant traits in the total surviving robots, respectively, and the solid lines are their fitting curves. The fitting results of the data indicate that the reason why such a population can survive in a periodically changing environment is because its genome can always match the environmental resources through mutation and reproduction. The vertical dotted lines in Fig. 3(d) represent the corresponding relationship between the peak value of different dominant traits and the peak value of the corresponding color resources. The distribution curve of robot dominant traits over time can be perfectly matched with the curve of the various color components of environmental resources, further demonstrating the population's strong environmental adaptability and the ability to survive for a long time.

The simulation experiment results presented the same conclusion as the robot experiment, as shown in Fig. 4, that only the population with both reproduction and mutation can survive for a long time in such a dynamically changing environment. Figure 4(a) shows the evolution of the population state and the landscape of resources over time in the simulation experiment. The environment settings of the simulations are the same as the robot experiments, and the robots with different traits are represented as circles in corresponding colors, which could consume diverse types of resources, therefore leaving shadows of different colors and depths in the environment. Figure 4(b) displays the four sets of experimental results corresponding to the robot experiments. In addition to the overall conclusion being consistent with the robot experiment, some differences in the details of the curve between the simulation experiment and the robot experiment could be found. Firstly, compared with the robot experiments, the conclusion of group survival did not change in the simulation experiments under the same conditions, but the survival time was much longer than that in the robot experiments. Then, under the experimental conditions where robots only had the ability to breed but no mutation occurred (magenta line in Fig. 4(b)), although the population in the simulation experiment eventually became extinct, there were more obvious fluctuations in the population size during the process. When the timestep is around 1800 and 3000 timesteps, there is a noticeable temporary increase in the population. The main reason for these differences above is the presence of noise in the real robotic system that does not exist in the simulation system.

Real robot systems have various sources of noise, including heterogeneity in the mechanical structure of robots, noise generated by color sensors when detecting environmental colors, and noise generated by the environmental platform when displaying color environments. In addition to noise introduced by individuals, noise generated during interactions between robots in a group is also a significant factor. When two robots approach each other, they will collide and produce physical effects, which differ significantly between real robot experiments and simulation experiments. For example, in real robot experiments, it may take a long time for two individuals to stop entangling after they meet, while in simulation experiments, it is much simpler. The existence of these noises leads to more complex situations for robots when adapting to the environment. In simulation experiments, individuals can survive longer than in real robot experiments because they have higher accuracy in moving along resource gradients, spend less time entangling when they meet, and have more accurate detection

of environmental colors. These are the reasons why the fluctuations of the magenta line in Fig. 4(b) are more obvious and agents could survival for a longer time in simulations. Therefore, although the overall conclusions of the robot experiments and the simulation experiments are consistent, there are differences in many details.

4. Conclusion

Researching the adaptive issues of robot active matter in complex environments can validate the effectiveness of the biological evolution theory in robot systems. It can also inspire exploration of the application direction of robot swarm systems. When a robot swarm is in a complex, dynamic, and unpredictable practical environment, how to make individuals and the swarm quickly adapt to such an environment is a practical scientific problem.[37] Examples of such environments include earthquake relief operations, microsurgery, and space exploration. These require the ability to adapt to complex unknown environments.

Based on the large-scale environment-coupled swarm robot experimental platform, the main evolutionary characteristics such as gene mutation, breeding and natural selection are introduced into the swarm robot system. Combining the differences and unique functional characteristics of robot swarms and organisms, and through special experimental designs of digital genes, mutation characteristics, and reproductive rules, we successfully verified that only a population with both breeding and mutation capabilities can adapt to periodic environment and survive for a long time. The effectiveness and reliability of this result have been verified through both robot experiments and simulation experiments.

Our work not only makes robot swarms a completer and more reliable experimental model of evolving systems but also addresses the practical scientific problem of how to make individuals and swarms quickly adapt to complex and dynamically changing environments. This provides new research ideas for the study of adaptive behavior of active matter systems.

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