ENGINEERING

Bio-inspired robotic collectives

A robotic system has been demonstrated in which the random motion of individual components leads to deterministic behaviour, much as occurs in living systems. Environmental and medical applications could follow. SEE LETTER P.361

METIN SITTI

In biological systems, large-scale behaviour can be achieved by the collective coupling and coordination of stochastically (randomly) moving small-scale components. For example, living cells aggregate and migrate collectively during the healing of wounds and when cancer spreads. Inspired by these biological mechanisms, on page 361, Li *et al.*[1] report a collective robotic system in which deterministic locomotion is a result of the stochastic movement of many loosely coupled, disc-shaped components. The results show that stochasticity offers a promising approach to developing large-scale, collective robotic systems that exhibit robust deterministic behaviour.

In Li and colleagues' system, the disc-shaped components cannot move independently of one another and cannot be manipulated individually. Moreover, each component can move only by oscillating along its radius, by expanding and contracting. The authors refer to this minimalistic approach as "particle robotics". In the absence of an external stimulus, the system can move only randomly. However, when the components are programmed to adjust their diameter in response to a varying environmental signal, there is collective locomotion towards the source of the signal.

Li *et al.* carry out experiments in which the particle-robotics system contains up to two dozen components, and simulations in which the system has as many as 100,000 components. The diameter of each component varies from 15.5 to 23.5 centimetres during the oscillations. The authors show that the system can achieve robust locomotion and object transport, as well as light-directed movement and obstacle avoidance (Fig. 1). Remarkably, they find that locomotion can be maintained even when 20% of the components malfunction, which highlights the robustness of the particle-robotics approach to individual component failures.

Previous studies have mainly considered components that can move independently of one another, can be manipulated individually, and that are based on relatively complex, deterministic designs[2–5]. Most of the previously reported collective robotic systems have limited flexibility in terms of allowable configurations, whereas those that are amorphous typically contain components with limited scalability. Moreover, many of these systems require some level of centralized control, which further restricts their capabilities and scalability.

In this regard, Li and colleagues' particle-robotics approach provides a promising alternative to other methods. In addition to being inspired by biological systems, the technique is motivated by statistical-physics phenomena, in which the global statistical behaviour of a large number of stochastic components can be modelled and controlled without the need to track each component. As a result, the approach has substantial advantages over other methods, especially when scaling up the number of components and scaling down the size of each one. Such scaling will be required for many future potential applications of collective robotic systems in exploration, construction and medicine.

Nevertheless, the authors' system has some drawbacks. First, if there is no environmental-signal gradient at the location of the aggregate of components, the system cannot move towards the source of the signal. Second, the components need to start from manually configured positions, because they cannot move independently to engage each other. Third, the experimentally demonstrated components are limited in number and are relatively slow and large; in the near future, the system should be extended to a larger number of components that are faster and much smaller (perhaps even down to the micrometre scale). And fourth, this technique is not suitable for tasks such as directed self-assembly and self-organization into complex, prespecified geometries, because of the stochastic nature of the aggregate and the random placement and coupling of the components.

Because of advances in small-scale robotics, it is possible to design and fabricate large numbers of stochastic or deterministic components that can exhibit collective and swarming behaviour[6] similar to that of the particle-robotics system. In the past few years, mobile micro-scale robotic swarms that have well-defined collective behaviour have been produced by

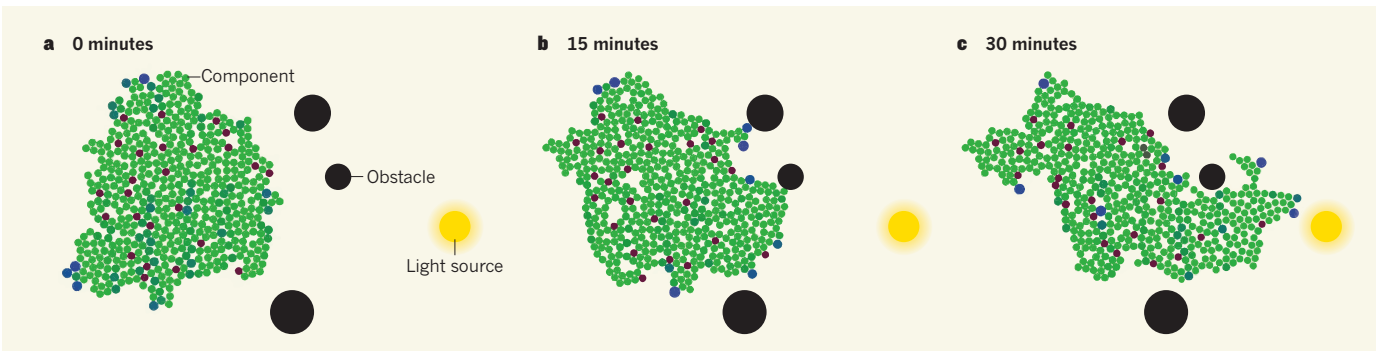

Figure 1 | An innovative collective robotic system. **a–c**, Li *et al.*[1] report a robotic system that is composed of many loosely coupled, randomly moving, centimetre-scale components. Each component can move only by oscillating along its radius, by expanding and contracting. The colour of the components represents their diameter, from minimum (green) to maximum (blue), during such oscillations. Malfunctioning components, which are used to test the robustness of the system, are depicted in maroon. The authors show that their system can exhibit deterministic locomotion towards an environmental signal — such as a light source — over time, while avoiding obstacles. (Adapted from Fig. 1f of ref. 1.)

engineering magnetic interactions between individual units. In general, the main strategy for controlling such swarms relies on the response of the units to remotely controlled global fields, such as magnetic fields[7,8]. Although it is then difficult to deal with each unit individually and locally, collective coupled interactions between the units can be globally controlled, resulting in programmable local interactions, self-assembly and collective behaviour. This method has been used to attain collective two-dimensional assembly, disassembly and manipulation of synthetic microrobotic swarms at the interface between air and water[9].

Li and colleagues' particle-robotics system, and most other collective robotic systems, work mainly in two dimensions. Extending such systems to three dimensions, with more-complex locomotive behaviour of components and their aggregates on surfaces or inside fluids, would increase their possible future applications. However, going to three dimensions would bring many hardware-design challenges for robust locomotion, aggregate stability, reversible and programmable component-attachment methods, miniaturization and control.

In the near future, it will be crucial to demonstrate potential high-impact engineering and medical applications of such collective robotic systems that would be impossible using other techniques. For example, swarms of stochastic bacterium-driven microrobotic swimmers could use the particle-robotics approach to deliver drugs to targeted, hard-to-reach regions inside the human body. Such swarms might, for example, be directed by the chemical gradients, oxygen gradients or changes in pH of cancerous-tissue environments[10]. Indeed, many studies[11,12] have already shown that collective bacterium-driven microrobotic swarms have potential applications in targeted drug delivery, medical diagnostics and environmental sensing. ■

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MEDICAL RESEARCH

Fighting cystic fibrosis with small molecules

In cystic fibrosis, ion-transport abnormalities cause problems in many organs. A small molecule that forms cell-membrane pores allowing ion transport shows therapeutic promise in human cells and a model of the disease. SEE LETTER P.405

DAVID N. SHEPPARD & ANTHONY P. DAVIS

In cystic fibrosis, abnormalities in the ion-channel protein CFTR cause problems in the transport of chloride (Cl^-) and bicarbonate (HCO_3^-) ions in the epithelial cells that line the airways of lungs, resulting in a build-up of mucus in these airways. This hinders the normal process that removes mucus and the inhaled bacteria trapped in it, and the resulting airway blockage leads to persistent infections and inflammation, which destroy lung tissue[1]. On page 405, Muraglia *et al.*[2] demonstrate that a small molecule called amphotericin B, which can form an ion channel in the cellular membrane of airway cells, restores ion transport and antibacterial defences when tested *in vitro* in human cells from people with cystic fibrosis and in an *in vivo* animal model of the disease.

Much progress has been made in developing new treatments for cystic fibrosis, and cocktails of three drugs that might slow disease progression are now in clinical trials[3,4]. A common defect in cystic fibrosis is the failure of CFTR to reach its location on the cell membrane, and two of the drugs help the protein to overcome this, with the third boosting ion transport through the channel. However, approximately 1,800 faulty versions of the CFTR-encoding gene associated with the disease have been identified so far, and this diversity of mutations might mean that drugs targeting CFTR will not work for everyone who has the disease[1].

Interest has therefore grown in trying to find widely applicable treatment options for cystic

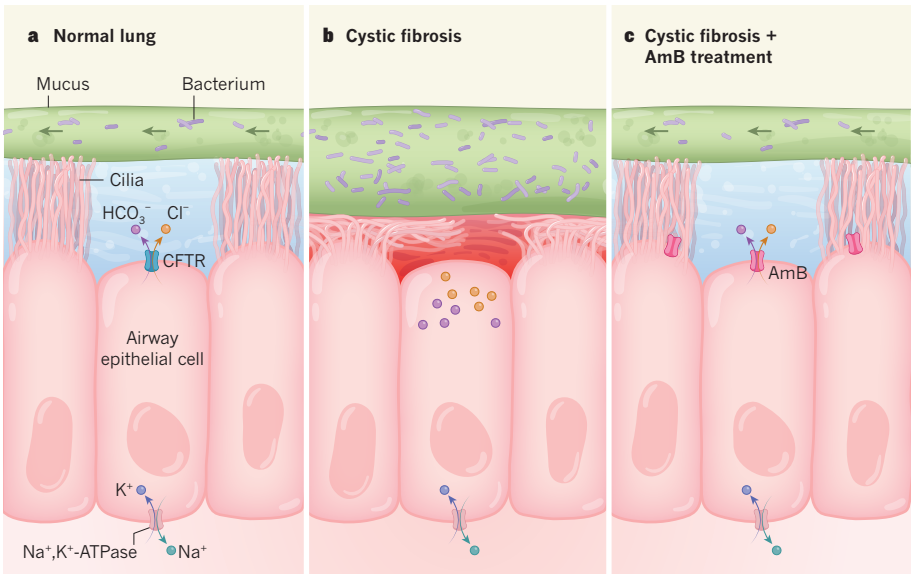

Figure 1 | Amphotericin B tackles lung problems in cystic fibrosis. **a**, Airway epithelial cells in lungs are bathed in a thin layer of airway-surface liquid (blue) on which mucus floats. The beating of cellular protrusions called cilia propel (green arrows) this mucus and trapped bacteria from the airways. Mucus removal, the killing of trapped bacteria and the maintenance of a normal volume of airway-surface fluid at physiological pH require the presence of bicarbonate (HCO_3^-) and chloride (Cl^-) ions in the surface liquid. These ions are secreted into the liquid through the activity of a network of ion-transporting cellular proteins (not all shown), including the Na^+, K^+-ATPase protein, located in the cell's tissue-facing (basolateral) membrane, and the protein CFTR, which is found in the liquid-facing (apical) membrane of certain airway epithelial cells and transports HCO_3^- and Cl^- out of the cell. **b**, In cystic fibrosis, CFTR is absent from some epithelial cells. This causes a build-up of cellular HCO_3^- and Cl^-, and the subsequent formation of airway-surface fluid that is more acidic (red) and of a smaller volume than normal[1,8]. The mucus is thicker than usual, and mucus removal and bacterial killing are abnormal[8]. **c**, Muraglia *et al.*[2] demonstrate in human cells and in a pig model of cystic fibrosis that treatment with the small molecule amphotericin B (AmB), which forms a non-selective ion channel, restores ion transport when CFTR is absent.