a control group that had no interventions[5].

Meriggi and colleagues estimate that their mobile vaccination campaign cost US$32 per delivered dose, and note that the figure would be even less, at $23 per delivered dose, if the intervention were implemented on a larger scale. This is indeed a highly cost-effective approach to promoting COVID-19 vaccination. However, the authors' claim that their approach is more cost-effective than alternative strategies to promote vaccination, particularly demand-creation approaches such as text messages or incentives, is more questionable. Many of those strategies were tested in higher-income countries where baseline vaccination rates were much higher than in rural Sierra Leone, making it harder to achieve comparable gains in vaccination rates.

Instead, the cost-effectiveness of the interventions tested in this study should be compared with alternative approaches to vaccine delivery and demand creation in low-income countries. As the authors rightly suggest, further testing of such approaches is necessary in these countries. Equally, the potential adverse consequences of shifting scarce health-care workers from health facilities to mobile sites should be considered when mobile campaigns are implemented on a large scale. A key question to ask in these studies would be, 'Which health-care services didn't get delivered today because a mobile campaign required staffing?'

Many people in low- and middle-income countries (as well as lower-income individuals in high-income countries) face barriers in accessing affordable and convenient health-care services. During the COVID-19 pandemic, the world learnt the worth of making vaccines easily accessible. What's needed is further experimentation with decentralized health-service delivery models, a stronger emphasis on the design of demand-creation approaches and greater integration of multiple health services – from childhood vaccinations to screening for infectious and chronic diseases – into mobile health-care delivery. These approaches might prove to be a winning formula for reducing health disparities and improving population health.

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Engineering

Complex motions emerge from robot interactions

Sebastian D. Huber & Kukka-Emilia Huhtinen

An array of robots has been set up so that pushes between them produce movements that do not conform to the usual laws of motion. Fascinating behaviour emerges from these interactions: wave phenomena known as solitons. **See p.528**

Anyone taking an introductory physics course learns a few basic principles that make it easier to describe the motion of objects. These are: the energy of a moving system is always conserved; for every action there is an equal and opposite reaction, a condition known as reciprocity; and whenever the system becomes too complicated to describe, the motion can be broadly explained in terms of a linear relationship between variables. On page 528, Veenstra *et al.*[1] report a system, known as a robotic metamaterial, for which none of the above assumptions holds, and which consequently moves in an intriguing way.

What is a robotic metamaterial? Most people have a clear idea of what a robot is: a device that can autonomously perform a prescribed task. Self-flying drones that perform as well as world-champion human drone pilots[2] and quadcopters that can cope with the loss of one,

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From the archive

Constantly quivering eyes let us see clearly, and a subject so large you'll need a wheelbarrow for the handbook.

50 years ago

Eye-Movements and Visual Perception. By R. W. Ditchburn — When we wish to scrutinise an object … we point our eyes towards the thing and hold them quite stationary — or so one might think. But even during periods of concentrated fixation, the eyes are never really still. They move constantly with three components of motion: a slight tremor … probably originating in the intrinsic noise of the extraocular muscles; slow drift … and intermittent, tiny, fast flicks … Our normal persistent perception of the visual world must depend on one or more of these apparently involuntary movements because if an optical device is used to hold an image more or less fixed on the retina, despite eye movements, the pattern seems to fade virtually completely within a few seconds. Isaac Newton was perhaps the first to recognise this necessity for a moving retinal stimulus. He noticed that pressing the side of the eyeball with a finger stimulates the retina mechanically, producing a coloured blob superimposed on the visual field; however "if the eye and the finger remain quiet these colours vanish in a second minute of time, but if the finger be moved with a quavering motion they appear again".

From *Nature* 22 March 1974

150 years ago

The man who jokingly said that he had to give up the study of chemistry when the science became so bulky that its Handbook required a wheelbarrow for its conveyance, expressed a truth which has been painfully felt by many scientific workers. With continual fresh additions to our knowledge, anything like a comprehensive grasp of a large science must become daily more and more difficult; but while this difficulty is generally felt, it occurs with special force in the science of chemistry. Chemistry, of all sciences, has perhaps the most unlimited capacity for development. Its subject is enormous, including the whole of nature, animate as well as inanimate.

From *Nature* 19 March 1874

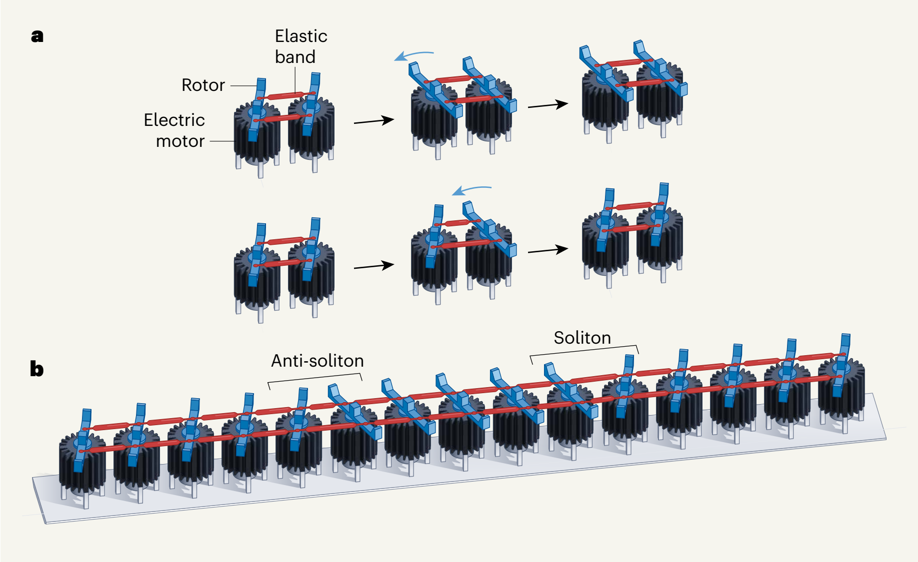

Figure 1 | A robotic system that produces solitons. **a**, Veenstra *et al.*[1] set up a row of 50 robotic units (not all are shown) each consisting of a rotor on top an electric motor. The interactions of the rotors were controlled by the motors, by magnetic fields (not shown) and by elastic bands connecting the rotors. At equilibrium, the rotors adopt one of two orientations: tilted to the left or to the right. When the left-hand rotor in a pair is flipped from one orientation to the other, the right-hand rotor also flips, and both adopt the new orientation (top). But when the right-hand rotor is flipped, the left-hand rotor does not, and the rotors return to their original orientation (bottom). **b**, When the rotors are connected in a row and then perturbed, a travelling boundary (known as a soliton, consisting of adjacent right- and left-tilted rotors) emerges between domains of left- and right-tilted rotors. Anti-solitons (adjacent left-and right-tilted rotors) also form.

two or even three of their propellers[3] are good examples of modern robots and what they can do. As for metamaterials, they are materials in which the constituent components and their interactions are engineered to give rise to behaviour that does not usually occur in nature.

Veenstra and colleagues' robotic metamaterial is neither a robot nor a metamaterial in the conventional sense. It consists of a row of simple mechanical rotors (the robotic units) that are coupled in two ways. Elastic bands connecting adjacent rotors mediate elastic interactions, enabling coordinated rotor motion that conforms to the energy-conserving, reciprocal and linear mechanics principles that are conventionally taught to physics students.

Furthermore, each rotor sits on top of an electric motor, which applies a torque to that rotor depending on the rotational position of its neighbours. This robotic part of the interaction is tuned so that, for any pair of neighbouring rotors, rotation of the left-hand rotor forces the right-hand rotor to turn in the same direction, but rotation of the right-hand rotor forces the left-hand rotor to turn in the opposite direction. In other words, non-reciprocity is introduced to the smallest constituents of the metamaterial (the pairs of rotors).

This robotic metamaterial has previously been shown to model interesting wave dynamics in the linear regime[4] – that is, the rotor motion produced waves described by equations that involve linear relationships. Those experiments were cleverly designed and resulted in neighbouring robotic units moving in a way that, at first sight, seems surprising. However, the linear dynamics linked the movements straightforwardly to the properties of the robotic units.

In the current study, Veenstra *et al.* further constrained the motion of the robotic units using magnetic fields, thereby inducing a strong, local non-linearity into the system. More specifically, the fields produced pairs of potential-energy wells, generating two stable states – characterized by a rotor being tilted to the left or to the right – in which each rotor can be at rest. This complicated the system substantially, so that the emerging behaviour of the metamaterial is hard to link to the behaviour of the individual constituents.

> **"The authors' robotic metamaterial is neither a robot nor a metamaterial in the conventional sense."**

The authors observed that, at equilibrium, all the rotors in the system are in the same state, tilted either to the left or to the right. When a rotor is nudged so that it flips to the other state, it bumps against its neighbour, making it flip as well. This launches a travelling boundary between domains of left- and right-tilted rotors, a type of mobile topological defect known as a soliton.

The solitons are produced for a wide range of parameters of the system, without any fine-tuning, as long as the strength of the coupling between rotors is above a certain threshold. The non-reciprocity of the rotor interactions ensures that solitons travel only in one direction. Moreover, solitons (consisting of adjacent right- and left-tilted rotors; Fig. 1) and anti-solitons (adjacent left- and right-tilted rotors) travel in the same direction with individually tunable velocities. The authors provided an insightful model of the motion, which allowed them to make testable predictions that were validated in the experiment.

Solitons have been studied in non-linear mechanical systems before[5,6]. The leap forward in the present work is that the energy needed to drive both perpetual travel of the solitons and the launching of successive solitons is provided by the robotic units and does not have to be input manually. This means that Veenstra and colleagues' robotic metamaterial could be used for processing and filtering of mechanical signals.

By introducing non-linearities into a driven, non-reciprocal system, the authors have opened the door to controlled investigations of the interactions of topological defects that are more complicated than solitons. The results might also provide clues about how to implement mechanical logic – the processing of mechanically encoded information – in soft robots.

Some people might say that the material devised by Veenstra and colleagues is a rather elementary robot, which is certainly true. The robotic units simply provide a controlled non-reciprocity, which can arise naturally, for instance, in biological systems[7] or in fluids[7,8]. But the point of the work is not to demonstrate elaborate robotics, but rather to showcase the strange physics that emerges beyond what the robots induce directly using their central processing units.

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