News & views

Engineering

Self-burying robot morphs wood to sow seeds

Samuel E. Mason & Naomi Nakayama

A natural seed has inspired the design of a robot that can bury itself in soil when exposed to rainfall. The mechanism relies on the shape-changing properties of wood — a simple and elegant example of sustainable innovation. **See p.463**

Wood swells in response to humidity — a tendency that makes the scales of pine cones close when wet[1]. Structures that change shape in this way are known as hygromorphs, and plants often use them to sense and respond to environmental changes. On page 463, Luo *et al.*[2] have optimized a hygromorphic structure to produce a robot that can plant seeds efficiently and sustainably. The mechanism draws inspiration from real seeds and the material is natural and renewable, allowing for harmless degradation of the robot after use.

Aerial seeding is a technique for sowing seeds by spraying them from an aeroplane, helicopter or drone. It is invaluable in remote areas in which soils need to be rejuvenated for agriculture or for land regeneration. However, the process is often inefficient and the rates at which seeds are established as plants can be low[3]. These limitations are addressed by using seed carriers, structures that improve germination efficiency by helping seeds to penetrate the soil.

Nature is full of inspiration for such carriers: for example, the seeds of the flowering plant *Erodium* are equipped with a curved tail that acts as a tool for self-burial. But, in practice, these natural seeds have a difficult time penetrating the ground — Luo *et al.* measured a success rate that was as low as 0% on some terrains. Inspired by these seeds' self-drilling potential, however, the authors used the hygromorphic nature of oak wood to design a robotic seed carrier that can drill into soil up to 80% of the time.

Both the authors' robot and the natural seed have a coiled body with a seed tip at one end. The other end of the *Erodium* seed has a tail that anchors the seed in the soil and changes shape in response to variations in the humidity of its environment. Luo *et al.* gave their robot three tails so that it is anchored more effectively than the *Erodium* seed, and generates greater rotational and thrust forces. Exposing these tails to water makes them change shape and unwind, creating a drilling action that places the seed safely below the soil surface. On drying, the tails rewind, pushing the seed farther into the soil (Fig. 1).

That Luo *et al.* could induce these shape changes in a wooden structure is surprising. They had to engineer the wood to have a high bending curvature, while maintaining high stiffness. Previously reported hygromorphic actuators (devices that convert energy into motion) have been made from synthetic materials[4], or from wooden particles embedded in synthetic materials[5]. One exception is a wooden actuator that uses two types of wood to passively rotate its own structure[6]. Luo and colleagues' system is simpler, and achieves rotational actuation using only one material.

There are strong arguments for using wood in such devices. Wood is a solid, comprising layers of cell walls arranged in a honeycomb-like structure. These layers make the material stiff, yet light, and hygromorphic — differential swelling across the wood tissue leads to changes in shape as the cells absorb water from their environment. Luo and colleagues' challenge, therefore, was in optimizing stiffness and curvature. They were able to engineer natural white-oak veneer so that it retained 36% of its stiffness while achieving a bending curvature 45 times that previously reported for wood-based actuators. They then placed the veneer on a 3D-printed mould to make the *Erodium*-inspired form.

The authors found that the processes of moulding and drying changed the curvature of the wood in different ways. The wood was moulded into shape while wet, and the curvature change permanently deformed the material, disrupting the alignment of fibres

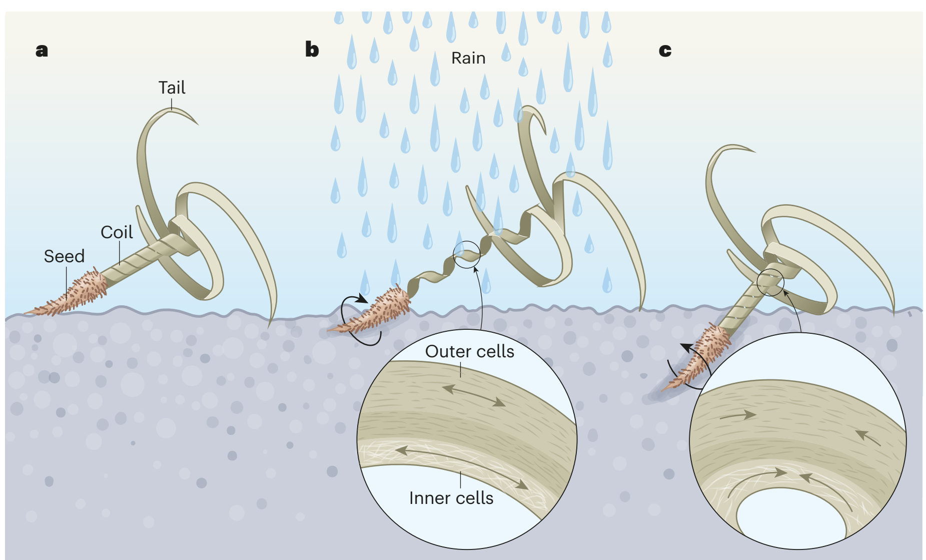

Figure 1 | A rain-driven robot that sows seeds sustainably. **a**, Luo *et al.*[2] designed a device that can drill seeds into soil using the shape-changing properties of a coiled body and three tails, all made from oak wood. **b**, When the robot is exposed to rainfall, the wood cells swell. Those on the inner surface change more than those on the outer surface, owing to deformation of the wood fibres during fabrication. This differential swelling unwinds the coil, drilling the seed into the soil. **c**, When the coil dries, the cells shrink, more so on the inner surface than on the outer surface. This causes the coil to wind up again, switching the direction of the torque and pushing the seed deeper into the soil.

between the inner and outer sides of the coil. As the wood dried, the cells all shrank, but those on the inner surface shrank more than those on the outer edge. This led to the shape change that made the whole structure rotate. Having understood the physical principles underlying this hygromorphic behaviour, Luo *et al.* designed a simple process that involved boiling the veneer in a chemical bath to improve mouldability, while maintaining the stiffness required for drilling into the soil.

The versatility of the design is particularly appealing; it comes from the authors' thorough understanding of the material. Using a combination of computational modelling and physical experiments, they tailored their seed carriers to deliver seeds with masses ranging from 52 to 75 milligrams. The mechanism remained the same for all seeds: moisture caused the cells to swell and the coil to unwind, drilling the payload down; the coil then wound up again as it dried, pushing the payload deeper underground.

Although these wooden robots have potential, they are not flawless. The manufacturing process involves positioning the veneer on the delicate 3D-printed mould and then carefully gluing the tails together. This manual process will need to be refined if it is to be scaled up in a way that could make the technology truly useful. Luo *et al.* used white oak because it is reasonably stiff, but this could be replaced with other types of wood if the fabrication process were adapted to involve stiffening (see, for example, ref. 7).

The authors' tests also seem to indicate that stormy weather severely compromises the efficiency of the device. Further work is needed to ensure that the robots can function in the potentially harsh, variable and remote environments for which they are intended.

There has been much talk of soft robotics using flexible materials[8], but hygromorphic wood does not quite fit this description. Actuators of this type fall into the realm of 'firm' robotics — devices made from relatively stiff materials that have the shape-changing behaviour of soft robots. These devices have the advantage of interacting with resistive substrates (such as soil) more easily than do soft robots. Thinking beyond seed carriers, the insight presented in this work could enable a range of hygromorphic wooden actuators, or contribute to developments in passively responsive architecture.

Luo and colleagues' bioinspired solution to the inefficiency of aerial seeding is a prime example of problem-led engineering. The authors' ability to tailor their seed carriers for different payloads and forces is impressive and shows that wood is still a state-of-the-art material. It also highlights the potential for natural materials to be highly controllable and functional, as well as sustainable.

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Medical research

For antibodies, sometimes less is more

Christoph Wülfing & Simon J. Dovedi

Antibodies that activate stimulatory or inhibitory receptors are of great therapeutic interest for the treatment of cancer or autoimmune diseases. It emerges that such antibodies work better if they don't bind to receptors too tightly. **See p.539**

Antibodies have a remarkable capacity to recognize specific parts of proteins called antigens, particularly those associated with disease or infection. B cells of the immune system make antibodies, and they can be generated to target any protein, engineered to tune their properties and produced at scale *in vitro*. Thus, they have become widely used therapeutics. Yu *et al.*[1] report on page 539 how antigen-binding strength determines the effectiveness of three antibodies used to treat tumours and autoimmune diseases, and the authors suggest that less is more.

In a therapeutic context, antibodies that target stimulatory or inhibitory receptors are used to regulate the function of immune cells (Fig. 1). Those that bind to a receptor and thereby impede the receptor's interaction with its usual binding partner (ligand) are called blocking antibodies. Antibodies that block the inhibitory receptors PD-1 and CTLA-4 have revolutionized cancer therapy by offering a way to activate tumour-targeting immune cells. By contrast, 'agonist' antibodies can function as synthetic ligands to activate a receptor.

Both types of antibody hold interest as clinical tools. Although the immune system can eliminate tumour cells, the tumour microenvironment is often immunosuppressive, with high expression of inhibitory receptors and ligands, and a lack of ligands for stimulatory receptors. Some of the current developments for cancer treatment are focused on antibodies that activate stimulatory immune receptors[2]. Yu and colleagues investigated clinically relevant agonist antibodies that target CD40, a stimulatory receptor on certain types of immune cell (myeloid and B cells), and CD137, which is also known as 4-1BB, a stimulatory receptor on T cells of the immune system.

Another area of therapeutic development focuses on self-destructive immune responses that cause autoimmune disease. To examine antibody-mediated suppression of autoimmunity, the authors investigated an antibody that stimulates inhibitory signalling in immune cells through PD-1.

The immune system generates high-affinity antibodies — their binding, as assessed by a measurement called a dissociation constant, is often in the picomolar range. This ensures long-lasting binding, which is important if blocking antibodies are to fulfil their role. However, the binding affinities of natural receptor–ligand interactions are weak and are often in the low micromolar range. Work on the main activating receptor of T cells, called the T-cell receptor, suggests that low affinities are optimal for receptor function[3]. Such low binding affinities enable a ligand to bind for long enough to enable the receptor to initiate a consecutive series of signalling steps, yet for a short enough length of time to enable one ligand molecule to subsequently engage many receptors to amplify the signal[3].

Yu and colleagues investigated whether an optimum intermediate affinity exists for agonist antibodies. The authors generated a range of agonist antibody variants that target CD40 with a large nanomolar range of binding affinities. The authors assessed these variants using mouse and human immune cells. They examined the activation of B cells and immune cells called dendritic cells, monitored the activation-associated proliferation of T cells