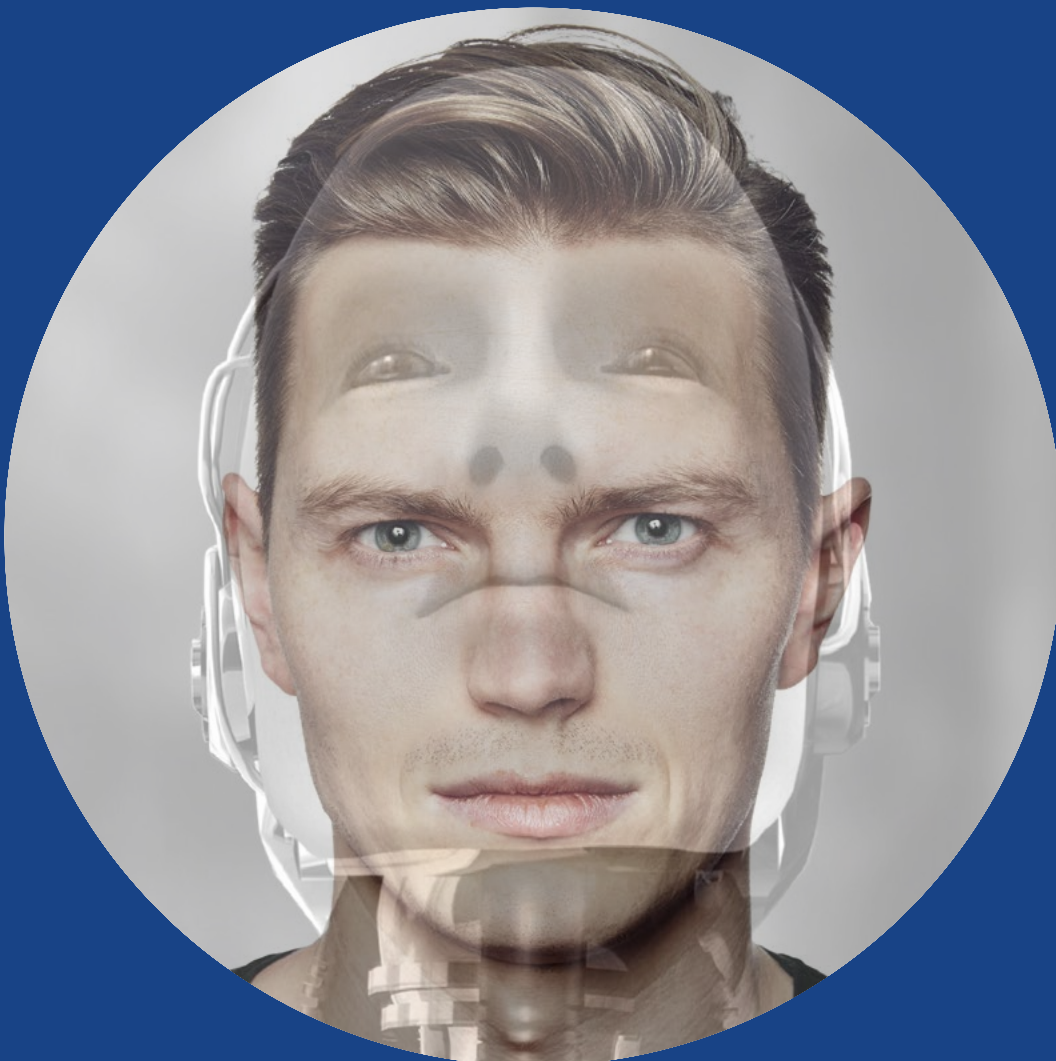
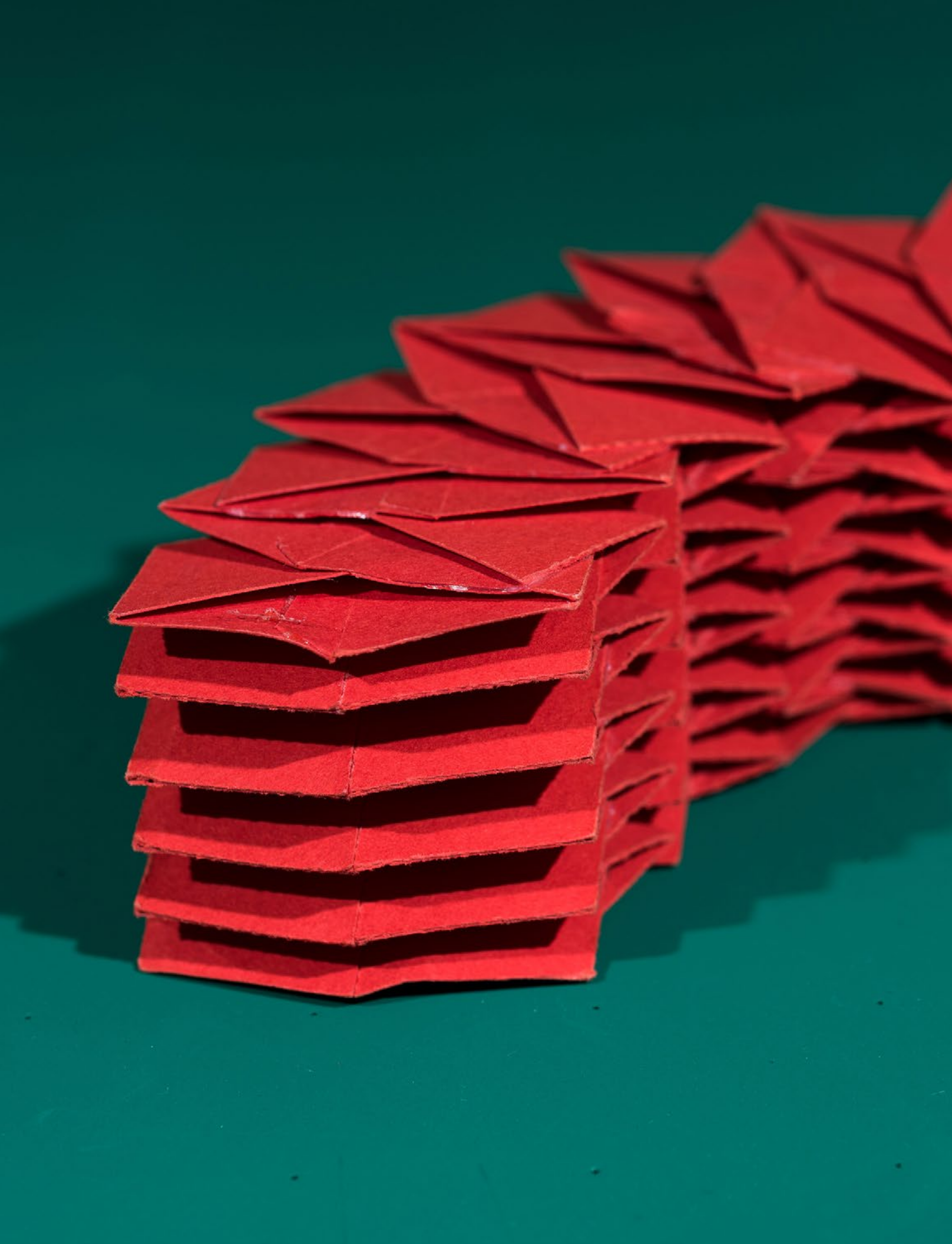


The Next Step

EXPONENTIAL LIFE

Robotics, Smart Materials, and Their Future Impact for Humans

JONATHAN ROSSITER



Opening image:
From shipping and construction to outer space, origami can put a folded twist on structural engineering. This origami structure is composed of twelve interlocking tubes that can fold flat for easy transportation.

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Jonathan Rossiter is Professor of Robotics at the University of Bristol and EPSRC Research Fellow. He is founder and head of the Soft Robotics Group at Bristol Robotics Laboratory. He was previously Royal Society and JSPS Research Fellow. He has been awarded over £17 million in research funding and has published over 130 peer-reviewed articles, patents and commercial licensing. His research interest centers on future robotics, and especially the emerging fields of soft robotics and smart materials. He has developed new technologies including biodegradable robots, natural affective touch, camouflage smart skins, shape-fixing composites, and multi-degree-of-freedom soft actuators. By developing such new technologies Jonathan Rossiter is working toward truly ubiquitous robotics. Over the next ten to twenty years we will see robotics become a core part of almost all parts of our lives, encompassing how we live, how we work, how we relax and how we maintain our health.

MORE ABOUT THE AUTHOR [+]

What is a robot? What is a smart material? How can these two have so much impact on our future lives? In this article we will examine the true potential of robotics, and soft-smart robotics in particular. These technologies are set to turn our perceptions of what a robot is, and how it can help us and the world we live in, upside down. Instead of thinking of robots as large, rigid, and resilient machines, we can view future robots as artificial robotic organisms that have properties mimicking, and greatly extending, the capabilities of natural organisms. The unique properties of softness and compliance make these machines highly suited to interactions with delicate things, including the human body. In addition, we will touch upon concepts in emerging robotics that have not been considered, including their biodegradability and regenerative energy transduction. How these new technologies will ultimately drive robotics and the exact form of future robots is unknown, but here we can at least glimpse the future impact of robotics for humans.

INTRODUCTION

The nineteenth century marked the acceleration and wide adoption of industrial processes. At the start of the century the Industrial Revolution was in mid-swing, and by the end we had developed the car and were just about to demonstrate powered flight. The impact on the lives of humans was massive; social and economic rules that governed travel, health care, manufacturing, working environments, and home life were rewritten. In the twentieth century this process was repeated with the Technology Revolution, but at a much faster rate. Technology moved from the laboratory and research institute to the home. The new realms of electronics, telecommunications, automation, and computation were the driving forces, rather than the mechanical systems of the previous century. In the early 1900s there were almost no telephones, but at the dawn of the millennium mobile phones were an everyday sight; computers were almost unheard of one hundred years ago, but have become universal. We are now at the cusp of a new technological shift of equal significance: the Robotics

Revolution. This revolution will place the twenty-first century at a pivotal position in history. More importantly it will irrevocably impact on all our lives and the lives of future generations.

But what is the Robotics Revolution and what will it really deliver? To answer that we must examine what a robot is; what new technologies, such as smart materials, are emerging that will change the definition of a robot; and how robots will affect the lives of people and the health of the planet. If we briefly revisit the two prior revolutions—the Industrial and Technology—these were characterized by developments of two very different concepts: the mechanical and the electrical. Robotics, on the other hand, exploits a fusion of the mechanical systems, electrical systems, and new methods of computation and intelligence. It is through the combination of the best from multiple existing and new technologies that a quite astonishing range of robots and robotic systems is being, and will be, developed.

ROBOTS: FROM COLD WAR THREAT TO FUTURE SAVIOR

A "robot" is often defined in terms of its capability—it is a machine that can carry out a complex series of actions automatically, especially one programmable by a computer. This is a useful definition that encompasses a large proportion of conventional robots of the kind you see in science-fiction films. This definition, and the weight of established cultural views of what a robot *is*, has an impact on our views of what a robot *could be*. The best indication of this can be seen by examining cultural attitudes to robots around the world. If we type in the word "robot" to the English language version of the Google search engine we obtain images that are almost exclusively humanoid, shiny, rigid in structure and almost clinical (see fig. 1a). They also include some rather dark and aggressive-looking military-type robots. These results are skewed significantly by the cultural corpus that Google uses to mine these opinions. If we undertake the same search on the Japanese language Google site (using ロボット, the Japanese word for robot) we get a different set of results, as shown in Figure 1b. These results show far more friendly and approachable robots with fewer human-like features and more cartoon, and animal, representations. The cause of this difference is historic and due to the post-war cultural entanglement of new technologies, and robotics in particular, in the Cold War. Robots became exemplars of an alien threat. In contrast Japan did not suffer these prejudices and robots were therefore seen as benign entities. The consequence of these historical and cultural differences on robotics development is profound: Western robotics is heavily entwined in military research while Eastern robotics is focused on assist, health care, and industry. This cultural background also perpetuates our biased views of what a robot should look like and how it should behave.

Now we have the opportunity to break away from these conventions. There is no need for a robot to be humanoid, to have limbs, to walk, or to talk. Rather, we can have a much wider interpretation of what a robot is. The boundaries between smart materials, artificial intelligence, embodiment, biology, and robotics are blurring. This is how robotics will really affect the human race over the next twenty to forty years. And what an impact we can expect! From robots that can monitor and repair the natural environment to nano robots to track and kill cancer, and from robots that will lead the way to planetary colonization to robot companions to keep us from loneliness in old age. There is no part of our society or life that will not be affected by future robotics. In short, they will become ubiquitous.

(a) SEARCHES FOR THE WORD "ROBOT" ON GOOGLE.COM AND (b) THE EQUIVALENT WORD "ロボット" ON GOOGLE.CO.JP.

FIGURE 1

(a)

(b)

Searches conducted 2016.10.08.

TOWARD UBIQUITOUS ROBOTIC ORGANISMS

Nature has always found ways to exploit and adapt to differences in environmental conditions. Through evolutionary adaptation a myriad of organisms has developed that operate and thrive in diverse and often extreme conditions. For example, the tardigrade (Schokraie et al., 2012) is able to survive pressures greater than those found in the deepest oceans and in space, can withstand temperatures from 1K (-272 °C) to 420K (150 °C), and can go without food for thirty years. Organisms often operate in symbiosis with others. The average human, for example, has about 30 trillion cells, but contains about 40 trillion bacteria (Sender et al., 2016). They cover scales from the smallest free-living bacteria, *pelagibacter ubique*, at around 0.5µm long to the blue whale at around thirty meters long. That is a length range of 7 orders of magnitude and approximately 15 orders of magnitude in volume! What these astonishing facts show is that if nature can use the same biological building blocks (DNA, amino acids, etc.) for such an amazing range of organisms, we too can use our robotic building blocks to cover a much wider range of environments and applications than we currently do. In this way we may be able to match the ubiquity of natural organisms.

To achieve robotic ubiquity requires us not only to study and replicate the feats of nature but to go beyond them with faster (certainly faster than evolutionary timescales!) development and more general and adaptable technologies. Another way to think of future robots is as *artificial organisms*. Instead of a conventional robot which can be decomposed into mechanical, electrical, and computational domains, we can think of a robot in terms of its biological counterpart and having three core components: a body, a brain, and a stomach. In biological organisms, energy is converted in the stomach and distributed around the body to feed the muscles and the brain, which in turn controls the organisms. There is thus a functional equivalence between the robot organism and the natural organism: the brain is equivalent to the computer or control system; the body is equivalent to the mechanical structure of the robot; and the stomach is equivalent to the power source of the robot, be it battery, solar cell, or any other power source. The benefit of the artificial organism paradigm is that we are encouraged to exploit, and go beyond, all the characteristics of biological organisms. These embrace qualities largely unaddressed by current robotics research, including operation in varied and harsh conditions, benign environmental integration, reproduction, death, and decomposition. All of these are essential to the development of ubiquitous robotic organisms.

The realization of this goal is only achievable by concerted research in the areas of smart materials, synthetic biology, artificial intelligence, and adaptation. Here we will focus on the development of novel smart materials for robotics, but we will also see how materials development cannot occur in isolation of the other much-needed research areas.

SMART MATERIALS FOR SOFT ROBOTS

A smart material is one that exhibits some observable effect in one domain when stimulated through another domain. These cover all domains including mechanical, electrical, chemical, optical, thermal, and so on. For example, a thermochromic material exhibits a color change when heated, while an electroactive polymer generates a mechanical output (i.e., it moves) when electrically stimulated (Bar-Cohen, 2004). Smart materials can add new capabilities to robotics, and especially artificial organisms. You need a robot that can track chemicals?—you can use a smart material that changes electrical properties when exposed to the chemical. You need a robotic device that can be implanted in a person but will degrade to nothing when it has done its job of work?—you can use biodegradable, biocompatible, and selectively dissolvable polymers. The "smartness" of smart materials can even be quantified. Their IQ can be calculated by assessing their responsiveness, agility, and complexity (for example, the number of phase changes they can undergo) (Cao et al., 1999). If we combine multiple smart materials in one robot we can greatly increase the IQ of its body.

Smart materials can be hard, such as piezo materials (Curie and Curie, 1881), flexible, such as shape memory alloys (Wu and Wayman, 1987), soft, such as dielectric elastomers (Pelrine et al., 2000), and even fluidic, such as ferrofluids (Albrecht et al., 1997) and electrorheological fluids (Winslow, 1949). This shows the great facility and variety of these materials, which largely cover the same set of physical properties (stiffness, elasticity, viscosity) as biological tissue. One important point to recognize in almost all biological organisms, and certainly all animals, is their reliance on softness. No animal, large or small, insect or mammal, reptile or fish, is totally hard. Even the insects with their rigid exoskeletons are internally soft and compliant. Directly related to this is the reliance of nature on the actuation (the generation of movement and forces) of soft tissue such as muscles. The humble cockroach is an excellent example of this; although it has a very rigid and hard body, its limbs are articulated by soft muscle tissue (Jahromi and Atwood, 1969). If we look closer at the animal kingdom we see many organisms that are almost totally soft. These include worms, slugs, molluscs, cephalopods, and smaller algae such as euglena. They exploit their softness to bend, twist, and squeeze in order to change

shape, hide, and to locomote. An octopus, for example, can squeeze out of a container through an aperture less than a tenth the diameter of its body (Mather, 2006). Despite their softness, they can also generate forces sufficient to crush objects and other organisms while being dextrous enough to unscrew the top of a jar (BBC, 2003). Such remarkable body deformations are made possible not only by the soft muscle tissues but also by the exploitation of hydraulic and hydrostatic principles that enable the controllable change in stiffness (Kier and Smith, 1985).

We now have ample examples in nature of what can be done with soft materials and we desire to exploit these capabilities in our robots. Let us now look at some of the technologies that have the potential to deliver this capability. State-of-the-art soft robotic technologies can be split into three groups: 1) hydraulic and pneumatic soft systems; 2) smart actuator and sensor materials; and 3) stiffness changing materials. In recent years soft robotics has come to the fore through the resurgence of fluidic drive systems combined with a greater understanding and modelling of elastomeric materials. Although great work has been done in perfecting pneumatic braided rubber actuators (Meller et al., 2014), this discrete component-based approach limits its range of application.

A better approach is shown in the pneunet class of robotic actuators (Ilievski et al., 2011) and their evolution into wearable soft devices (Polygerinos et al., 2015) and robust robots (Tolley et al., 2014). Pneunets are monolithic multichamber pneumatic structures made from silicone and polyurethane elastomers. Unfortunately hydraulic and pneumatic systems are severely limited due to their need for external pumps, air/fluid reservoirs, and valves. These add significant bulk and weight to the robot and reduce its softness. A far better approach is to work toward systems that do not rely on such bulky ancillaries. Smart materials actuators and sensors have the potential to deliver this by substituting fluidic pressure with electrical, thermal, or photonic effects. For example, electroactive polymers (EAPs) turn electrical energy into mechanical deformation. Figures 2 and 3 show two common forms of EAP: the dielectric elastomer actuator (DEA) (Pelrine et al., 2000) and the ionic polymer actuator (IPA) (Shahinpoor and Kim, 2001). The DEA is composed of a central elastomeric layer with high dielectric constant that is sandwiched between two compliant electrode layers.

Clockwise, from top left: the protozoa *Euglena flagellate*; the cosmopolitan tardigrade *Milnesium tardigradum*; and the mimetic octopus *Thaumoctopus mimicus.*

When a large electric field (of the order MV/m) is applied to the composite structure, opposing charges collect at the two electrodes and these are attracted by Coulomb forces, labelled σ in Figure 2. These induce Maxwell stresses in the elastomer, causing it to compress between the electrodes and to expand in the plane, labelled ε in Figure 2. Since Coulomb forces are inversely proportional to charge separation, and the electrodes expand upon actuation, resulting in a larger charge collecting area, the induced stress in the DEA actuator is proportional to the square of the electric field. This encourages us to make the elastomer layer as thin as possible. Unfortunately, a thinner elastomer layer means we need more layers to make our robot, with a consequently higher chance of manufacturing defect or electrical breakdown. Because DEAs have power density close to biological muscles (Pelrine et al., 2000), they are good candidates for development into wearable assist devices and artificial organisms.

FIGURE 2. (a) UNACTUATED AND (b) ACTUATED STATES OF A SOFT DIELECTRIC ELASTOMER ACTUATOR

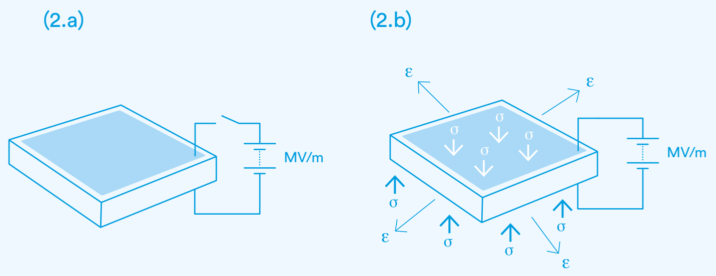
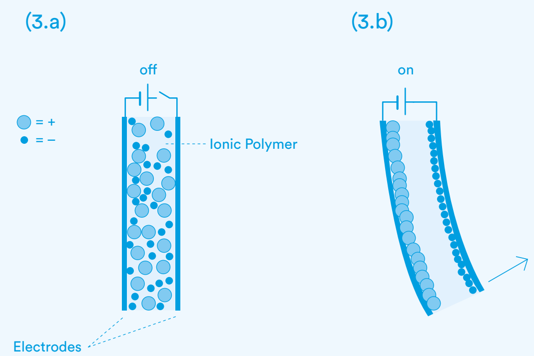


FIGURE 3. (a) UNACTUATED AND (b) ACTUATED STATES OF AN IONIC POLYMER ACTUATOR



FIGURES 2, 3

Ionic polymer actuators, on the other hand, are smart materials that operate through a different electromechanical principle, as shown in Figure 3. The IPA is fabricated from a central ionic conductor layer, again sandwiched by two conducting electrodes, but in contrast to DEAs the electric field is much lower (kV/m) and therefore the electrodes must be more conductive. When an electric field is applied, free ions within the ionic conductor move toward the electrodes where they collect. The high concentration of ions at the electrodes causes them to expand as like-charges repel due to local Coulomb forces. If the cations (+) and ions (-) are significantly different in size and charge, there will be a mismatch in the expansion of the two electrodes and the IPA will bend. The advantage of the IPA is that it operates at much lower voltages than the DEA, but it can only generate lower forces. A more recent addition to the smart materials portfolio is the coiled nylon actuator (Haines et al., 2014). This is a thermal actuator fabricated from a single twist-insertion-buckled nylon filament. When heated, this structure contracts. Although the nylon coil actuator has the potential to deliver low-cost and reliable soft robotics, it is cursed by its thermal cycle. In common with all other thermal actuators, including shape memory alloys, it is relatively straightforward to heat the structure (and thereby cause contraction of the muscle-like filament) but it is much more challenging to reverse this and to cool the device. As a result, the cycle speed of the nylon (and SMA) actuators is slow at less than 10Hz. In contrast, DEAs and IPAs have been demonstrated at 100's of Hz, and the DEA has been shown to even operate as a loudspeaker (Keplinger et al., 2013).

The final capability needed to realize the body of soft robotic organisms is stiffness change. Although this may be achieved through muscle activation, as in the octopus, there are a number of soft robotic technologies that can achieve stiffness modulation independent of actuation. These include shape memory polymers (SMP) and granular jamming. SMPs are polymers that undergo a controllable and reversible phase transition from a rigid, glassy state to the soft, rubber shape (Lendlein et al., 2002). They are stimulated most commonly through heat, but some SMPs transition between phases when photonically or electrically stimulated. The remarkable property of SMPs is their ability to "memorize" a programmed state. In this way an SMP robot can be made to transition between soft and hard, and when the operation is complete it can be made to automatically return to its pre-programmed shape. One exciting possibility of SMPs is to combine them with actuators that are themselves stimulated by the same energy source. For example, a thermally operated shape memory polymer can be combined with a thermal SMP to yield a complex structure that encompasses actuation, stiffness change, and memory in one unit driven solely by heat (Rossiter et al., 2014). Granular jamming, in contrast to SMP phase change, is a more mechanical mechanism (Amend et al., 2012). A compliant chamber is filled with granular materials and the stiffness of the chamber can be controlled by pumping a fluid, such as air, into and out of it. When air is evacuated from the chamber, atmospheric pressure due to the within-chamber vacuum cases the granules to compress together and become rigid. In this way a binary soft-hard stiffness changing structure can be made. Such a composite structure is very suited to wearable assist devices and exploratory robots.

ROBOTS WHERE YOU DON'T EXPECT THEM

Having touched above on the technologies that will give us a new generation of robotics, let us now examine how these robots may appear in our lives and how we will interact, and live, with them.

Smart Skins

The compliance of soft robotics makes them ideally suited for direct interaction with biological tissue. The soft-soft interactions of a soft robot and human are inherently much safer than a hard-soft interface imposed by conventional rigid robots. There has been much work on smart materials for direct skin-to-skin contact and for integration on the human skin, including electrical connections and electronic components (Kim et al., 2011). A functional soft robotic second skin can offer many advantages beyond conventional clothing. For example, it may mimic the color-changing abilities of the cephalopods (Morin et al., 2012), or it may be able to translocate fluids like the teleost fishes (Rossiter et al., 2012) and thereby regulate temperature. The natural extension of such skins lies in smart bandages to promote healing and to reduce the spread of microbial resistance bacteria by reducing the need for antibiotics. Of course, skins can substitute for clothing, but we are some way from social acceptance of second-skins as a replacement for conventional clothing. If, on the other hand, we exploit fibrous soft actuation technologies such as the nylon coil actuator and shape memory alloy-polymer composites (Rossiter et al., 2014), we can weave artificial muscles into fabric. This yields the possibility of active and reactive clothing. Such smart garments also offer a unique new facility: because the smart material is in direct contact with the skin, and it has actuation capabilities, it can directly mechanically stimulate the skin. In this way we can integrate tactile communication into clothing. The tactile communication channel has largely been left behind by the other senses. Take, for example, the modern smartphone; it has high bandwidth in both visual and auditory outputs but almost non-existent touch stimulating capabilities. With touch-enabled clothing we can generate natural "affective" senses of touch, giving us a potentially revolutionary new communication channel. Instead of a coarse vibrating motor (as used in mobile phones) we can stroke, tickle, or otherwise impart pleasant tactile feelings (Knoop and Rossiter, 2015).

Assist Devices

If the smart clothing above is able to generate larger forces it can be used not just for communication but also for physical support. For people who are frail, disabled, or elderly a future solution will be in the form of power-assist clothing that will restore mobility. Restoring mobility can have a great impact on the quality of life of the wearer and may even enable them to return to productive life, thereby helping the wider economy. The challenge with such a proposition is in the power density of the actuation technologies within the assist device. If the wearer is weak, for example because they have lost muscle mass, they will need significant extra power, but the weight of this supplementary power could be prohibitively expensive. Therefore the assist device should be as light and comfortable as possible, with actuation having a power density significantly higher than biological muscles. This is currently beyond the state-of-the-art. Ultimately wearable assist devices will make conventional assist devices redundant. Why use a wheel chair if you can walk again by wearing soft robotic Power Pants?

Medical Devices

We can extend the bio-integration as exemplified by the wearable devices described above *into* the body. Because soft robotics is so suitable for interaction with biological tissue it is natural to think of a device that can be implanted into the body and which can interact physically with internal structures. We can then build implantable medical devices that can restore the functionality of diseased and damaged organs and structures. Take, for example, soft tissue cancer that can affect organs ranging from the bowels and prostate to the larynx and trachea. In these diseases a typical treatment involves the surgical excision of the cancer and management of the resulting condition. A patient with laryngeal cancer may have a laryngectomy and thereafter will be unable to speak and must endure a permanent tracheostomy. By developing and implanting a soft robotic replacement organ we may restore functional capabilities and enable the patient to once again speak, swallow, cough and enjoy their lives. Such bio-integrating soft robotics is under development and expected to appear in the clinic over the next ten to fifteen years.

Biodegradable and Environmental Robots

It is natural to extend the notion of bio-integration from the domestic (human-centric) environment to the natural environment. Currently robots that operate in the natural environment are hampered by their very underlying technologies. Because the robots are made of rigid, complex, and environmentally harmful materials, they must be constantly monitored. When they reach the end of their productive lives they must be recovered and safely disposed of. If, on the other hand, we can make the robots totally environmentally benign, we can be less concerned with their recovery after failure. This is now possible through the development of biodegradable soft robotics (Rossiter et al., 2016). By exploiting smart materials that are not only environmentally safe in operation, but which safely degrade to nothing in the environment, we can realize robots that live, die, and decay without environmental damage. This changes the way we deploy robots in the environment: instead of having to track and recall a small number of environmentally damaging robots we can deploy thousands and even millions of robots, safe in the knowledge that they will degrade safely in the environment, causing no damage. A natural extension of a biodegradability robot is one that is edible. In this case an edible robot can be eaten; it will do a job of work in the body; and then will be consumed by the body. This provides a new method for the controlled, and comfortable, delivery of treatments and drugs into the body.

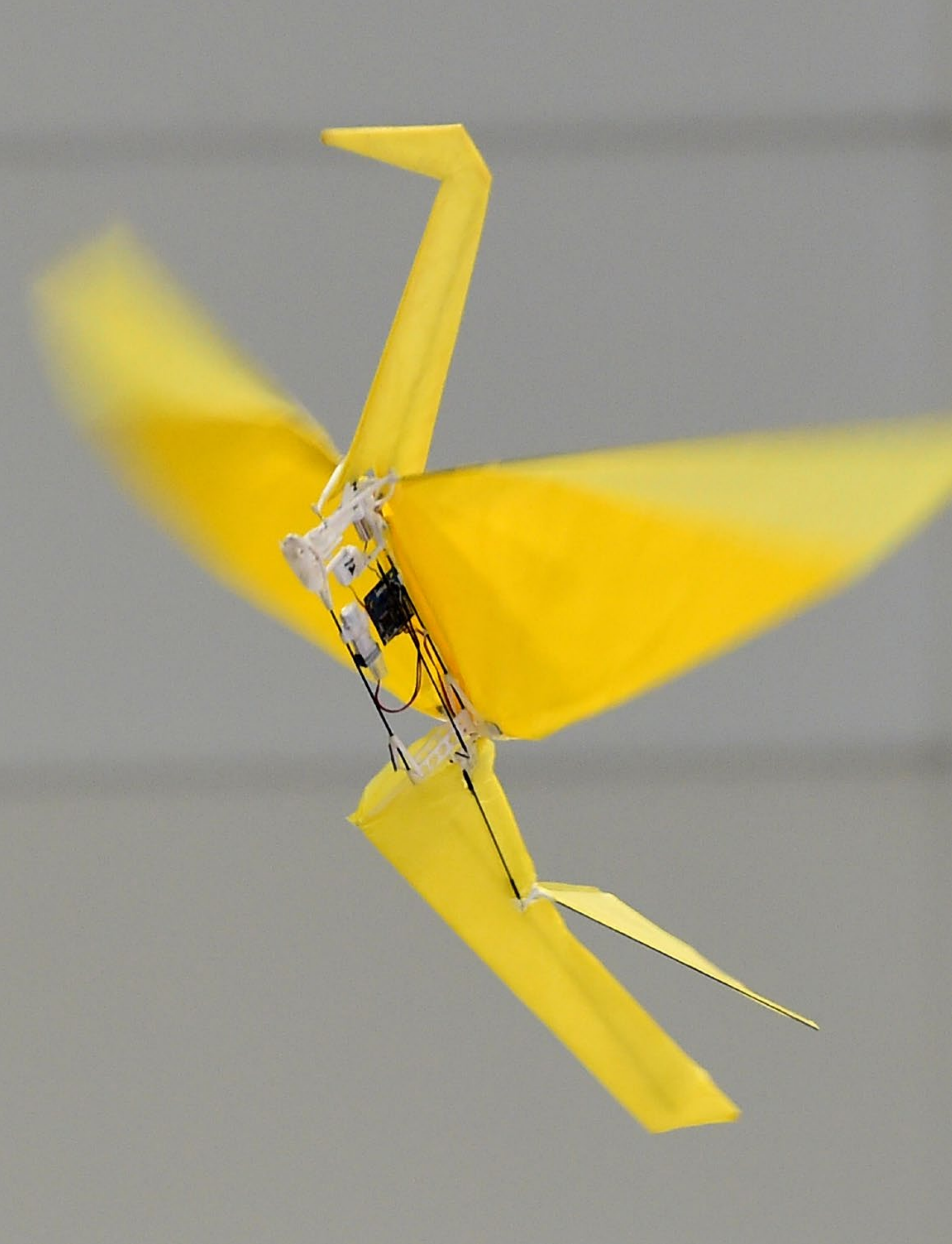
Intelligent Soft Robots

All of the soft actuators described above operate as transducers. That is, they convert one energy form into another. This transduction effect can often be reversed. For example, dielectric elastomers actuators can be reconfigured to become dielectric elastomer generators (Jin et al., 2011). In such a generator the soft elastomer membrane is mechanically deformed and this results in the generation of an electrical output. Now we can combine this generator effect with the wearable robotics described above. A wearable actuator-generator device may, for example, provide added power when walking up hill, and once the user has reached the top of the hill, it can generate power from body movement as the user leisurely walks down the hill. This kind of soft robotic "regenerative braking" is just one example of the potential of bidirectional energy conversion in soft robotics. In such materials we have two of the components of computation: input and output. By combining these capabilities with the strain-responsive properties inherent in the materials we can realize robots that can compute with their bodies. This is a powerful new paradigm, often described in the more general form as embodied intelligence or morphological computation (Pfeifer and Gómez, 2009). Through morphological computation we can devolve low-level control to the body

“Why can’t we write the entire twenty-four volumes of the Encyclopaedia Britannica on the head of a pin?”

RICHARD FEYNMAN (1918–88)
US theoretical physicist, in the famous lecture “There’s Plenty of Room at the Bottom,” which he gave in 1959 at the annual meeting of the American Physical Society.

Demonstration of an origami paper crane weighing only 32 grams, at the 2015 International Robot Exhibition in Tokyo.



of the soft robot. Do we therefore need a brain in our soft robotic organism? In many simple soft robots the brain may be redundant, with all effective computing being performed by the body itself. This further simplifies the soft robot and again adds to its potential for ubiquity.

CONCLUSIONS

In this article we have only scratched the surface of what a robot is, how it can be thought of as a soft robotic organism, and how smart materials will help realize and revolutionize future robotics. The impact on humans has been discussed, and yet the true extent of this impact is something we can only guess at. Just as the impact of the Internet and the World Wide Web were impossible to predict, we cannot imagine where future robotics will take us. Immersive virtual reality? Certainly. Replacement bodies? Likely. Complete disruption of lives and society? Quite possibly! As we walk the path of the Robotics Revolution we will look back at this decade as the one where robotics really took off, and laid the foundations for our future world.

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