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Interview with Robert Shepherd: On Soft Robots, Biomimetics, and Beyond

KK: Before starting with the general discussion on active matter, we would like to discuss more specifically the field you are researching, soft robotics, and how this field is situated in relation to active matter. How do you see yourself in this field? How do you consider the various materials or the various categories of matter – adaptive matter or programmable matter – which are being employed within this field of research?

RS: Adaptive matter and programmable matter are two different characterizations, and they are also employed differently in soft robotics. Here one has to recall that this differentiation is not exhaustive; there are several characterizations to add to this description of materials, namely, smart materials, adaptive (or adapted) matter, programmable matter, and so on.¹ For me, programmable matter and adaptive matter are different things. Programmable matter is prescribed to respond in a particular way. Adaptive matter should be able to change how it responds. To give an example for programmable matter, one can take origami [Holmes 2019]: you fold it so that, when you apply particular stress and then release it, it unfolds into the same shape. One can get better at making it respond differently, but traditionally it is mostly programmed to do a task based on one input. Adaptive structure can assess what is happening to it and change how it responds based on this assessment. This is how I differentiate adaptive and programmable matter. The term ‘smart matter’ is a bit of a catch-all. All of these materials are smart, one can say. What soft robotics does is that it takes advantage of all of these properties and puts them into a device for performing work that you would think a robot would perform. We want these robots to be autonomous, in the sense that they can make decisions based on their environmental conditions with the least amount of human input as possible. But, having said that, you can still use programmable matter to form the basic motion of the device. Take,

¹ On the blurry distinction between ‘matter’ and ‘materials’ in this discourse, see the introduction to this volume.

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for example, our work on a walking quadruped (see Fig. 1),² which I would say is programmable. When you apply pressure to it, it obtains curvature. You could say that it is programmable matter, since based on that input it has this or that curvature. But if you apply a different amount of pressure in another place, and all of the sudden it obtains a different shape, perhaps then one may call it adaptive. It is a blurry line at this point. But it is all smart. There is a mechanical intelligence programmed in here – or rather even a mechanical computation, or a material computation. It is as if there is a material computer that inputs stress and outputs a mechanical force and strain profile depending on the situation. That is what makes it different than ‘normal’ robots, which for example are moving something; when another object gets in the way they just crush it – for example, when a banana is in the way, it just squishes it. The robots in soft robotics are very different than normal robots because their material is doing the computation.

MF: You have mentioned several subjects to which we will return later. I want to concentrate on the first topic you mentioned: soft robots. You describe soft robots as those composed of soft mechanisms and soft chassis.³ As you said, hard machines, the ‘regular,’ ‘normal’ robots, can move objects from one place to another but cannot cope with changing conditions and environments. Soft robotics offers another point of view. How do you see this new conception of the machine stemming from soft robotics? In some of your papers you give several characteristics that are not usually associated with machines, like self-healing or being composed of autonomous materials [Mishra et al. 2020; Wallin et al. 2017; Tolley et al. 2014; Bekey 2005, pp. 1–25]. What are the differences between the old conception of the machine and the new one?

RS: One may say that the machine is something like a lever, it is stiff, and this mechanical advantage allows you to lift heavy things. These are traditionally the conceptions people associate with machines. But one should make a distinction between robots and machines. The reason I have done that is to work in the robotics community, as they have a particular vision of what a robot is. The main difference between robot and machine is the existence of sensors for robots. As I see it, the usage of ‘robot’ means sensors integrated with a computer to control the response of the machine. To me that

² See [Shepherd et al. 2011, p. 20400]: The quadruped is a “soft robot, composed exclusively of soft materials (elastomeric polymers), which is inspired by animals (e.g., squid, starfish, worms) that do not have hard internal skeletons. Soft lithography was used to fabricate a pneumatically actuated robot capable of sophisticated locomotion (e.g., fluid movement of limbs and multiple gaits). This robot [...] uses no sensors, only five actuators, and a simple pneumatic valving system that operates at low pressures [...]. A combination of crawling and undulation gaits allowed this robot to navigate a difficult obstacle.”

³ Note by Robert Shepherd: The difference between soft robots and ‘normal’ ones may be that they (i.e., soft robots) routinely combine the chassis and the mechanisms into one (embodiment).

Fig. 1: Cycle of pressurization and depressurization of a quadrupedal soft robot, which results in undulation. From: [Shepherd et al. 2011, 20401, Fig. 2]. © The Authors of [Shepherd et al. 2011].

is a robot. For the sake of simplicity, one could say that a ‘machine’ has no sensors. You apply input and it operates according to this input. Whereas for robots there are sensors that can respond differently based on the situation – in order to enable better control. In a nutshell, machine without sensors; robot sensors with integrated computer. The question hence arises: how are these soft machines and soft robots different from existing machinery and existing robots?

To give an example: One can consider human beings as skeletons with skin, organs, sensors, and a brain. Our brain is not just in the head, it is distributed. For a long time I was thinking we need to make a soft robot that is totally soft, like an octopus, as this is very adaptive. If one adds a skeleton, it is not adaptive anymore. But in fact there are a lot of advantages to having deformable tissue on a hard skeleton. We have the ability to sense very well. If I damage myself, I can detect it. If I get a blunt trauma, my skin can actually be fine but my bone on the inside will crack. Being able to feel that damage is important.

If you have these endoskeletal soft robots moving around, interacting with people, one of the things one would wish or require from these robots is an ability to self-heal, which is a challenge for robotics. Everybody wants robots that can walk around and operate for days. But they may get damaged. And when they get damaged, they are going to behave differently. Their control systems are going to adapt to that. But this ability to sense inside of a robot’s ‘flesh’ does not exist right now. We will need this and self-healing for better control.

MF: You have just talked about self-healing, another property that you deal with in your research is shape memory activation (see Fig. 2).⁴ These are properties that might seem to be inspired by nature. What is actually the relationship between nature, biology, and your approach to robotics? Does one need to imitate all of nature’s architecture or is it enough to be inspired only by several ‘good’ properties?

RS: We obviously do not need robots with reproductive organs. Maybe one does not need all these extra abilities either. But the crucial point is that at best, rather than mimicking nature, we are inspired by it. We cannot make muscle. Some people are growing it into robots, but we certainly cannot mix some chemicals together and then have something that acts like muscle. Having said that, I also believe that almost nobody is able to do something that is non-bioinspired because this inspiration is around us all the time. Everything we do is by necessity nature-inspired.

KK: I would like to focus on the relation between structural hierarchies in biological materials and in synthetic materials. One may say that biological systems operate as

⁴ See, for example: [Van Meerbeek et al. 2016].

Fig. 2: Shape memory actuation: a compressed cylinder of metal-elastomer composite expanding into a cuboid after melting the metal foam. Adapted from: [Van Meerbeek et al. 2016, p. 2804, fig. 3]. © 2016 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

multiscale chemomechanical feedback processes on various levels and through various hierarchies. They can adapt and develop because there is no predetermined program and not everything is controlled. Hence, an emergent structure may appear, as there is a kind of instability in the system itself. Does the new approach you are delineating with soft robotics also point toward this complexity of structure?

RS: Complexity and emergence of complexity certainly arise in nonequilibrium structures. The problem is that the number of devices and elements in our designs right now is just too small to expect an emergence of anything totally unexpected. Right now, we are not dealing with emergence or complexity this way. Eventually – hopefully – we will be able to do that. I think we can use additive manufacturing to get out a lot of the bottom-up assembly that happens in nature, but it would not have the resolution or complexity found there.

I believe a way to reformulate your question would be to ask what is the future of smart materials? To give an example, in our bodies we are constantly using fluid transport to operate. So we deliver sugar and we burn that sugar and our muscles contract. That is impractical in a car and in most things today because the surface-area-to-volume ratios are too low. For us to operate we have the very high surface-area-to-volume ratios of our blood. Our arteries, veins, and capillaries are distributing energy and removing energy (or removing waste) very efficiently. But if you were to ask an engineer to build something like us they would say that it is not possible or that it would not work well. But we human beings can have these abilities, because we self-assemble into these ‘impossible’ structures. So a possible solution to this problem would be to construct materials or robots with soft batteries, or in other words to think about embodied energy (see the lecture: [Shepherd 2019]). Explicitly, embodied energy

Fig. 3: One half of a disassembled ‘fish’ robot showing how the pumps and control hardware are housed internally. Material from: [Aubin et al., 2019, p. 55, fig. 5b], Springer Nature.

is a composite where the energy is part of the composite. We are working on a project on robot blood where the fluids are used to transmit force (see Fig. 3).⁵ You inflate this leg and it bends – this is done with air but you could also do it with liquid. If the liquid can also store energy it becomes multifunctional. You could also imagine doing this with a solid-state energy storage system in a rubber housing. A lot of work in the future is going to be on storing and packing as much energy as you can into every cubic millimeter of volume.

KK: Can one consider it as structurally stored energy?

RS: Yes, that is one example. But the structure is more than just a structure; it is also the actuator or the sensor, or ideally structure–actuator–sensor altogether. Which is also one of the benefits of a soft robot: it is the structure but it is also the actuator.

⁵ [Aubin et al. 2019, p. 51]: “Modern robots lack the multifunctional interconnected systems found in living organisms and are consequently unable to reproduce their efficiency and autonomy. Energy-storage systems are among the most crucial limitations to robot autonomy, but their size, weight, material and design constraints can be re-examined in the context of multifunctional, bio-inspired applications. Here we present a synthetic energy-dense circulatory system embedded in an untethered, aquatic soft robot. [...] this synthetic vascular system combines the functions of hydraulic force transmission, actuation and energy storage into a single integrated design.”

The idealized case is that the material is already structured, and the whole assembly of functions is already inscribed in it. We have to make compromises currently, but ultimately that is what we would like. I think 3D printing allows us to get there too.

MF: I want to discuss 3D printing in more detail. Three-dimensional printing may be seen as biomimicry in a certain way. This brings me back to an earlier question: to which level do we want to mimic nature? And, if we return to the question on emerging structures, can one imagine a scenario where one only prints the basic structure, when afterward something, a more complicated structure, will emerge?

RS: I think the future is in the application of 3D printing to robotics. The past has been about programmable matter. The present is a combination of the two. People have been growing tissue on 3D printed scaffolding for a long time. Not just through 3D printing but also through molding things. There is a difference between additive manufacturing and 3D printing. Three-dimensional printing is always additive manufacturing but additive manufacturing is not always 3D printing. Any time you are adding a material to something, that is, additive manufacturing. But 3D printing offers the most freedom in design. But one has to recall the idea of growing muscle on a scaffold and then using the muscle as an actuator in a robot: this is new.

Another concept in 3D printing is when you try to embed dynamics in the structures so it will move – to embed a fourth dimension, some people would say, as it responds differently based on inputs. I certainly believe that future research will be more about 3D printing structures where there are also actuators, which are also sensors.

To your point, however, using a 3D printed structure to nucleate more complex or nanostructured architectures is an exciting area of research.

MF: What you are proposing here is that the 3D printed material would also be an actuator, in a sense that it can be considered as four-dimensional (4D) printing, that is, as printing a material which is adaptive, specific to the environment, which does not have a fixed, ‘programmed’ behavior from the beginning.

RS: Yes, this is what I would say 4D printing is now. Honestly, though, I do not really like the term. I think it implies something more grandiose than what is mostly done. That is not saying it is not exciting, but does not it sound like you are warping through space? Anyway, yes, if you incorporate the ability for the structure to also sense and change its actuating response based on what it is sensing, you are not only printing a robot, you are actually printing a robotic material.

KK: If I may highlight another aspect of this adaptivity, another aspect of 3D printing concerns the geometry of what is printed. Three-dimensional printing is ultimately printing geometry. What are the geometrical properties that are taken into account when printing? Should one print the whole geometric structure? Especially when it comes to biological materials, if one prints an organ. At what level of detail do we actually need to print?

RS: When one talks about the 3D printing of tissues, one can definitely consult the work of Jennifer Lewis (Lewis Lab), who works in that direction quite a bit. An area that this community is working on is organoids, such as groups of cells that are representative of an organ, but they are not the whole organ. Similar to a bunch of liver cells, when one makes tests and sees how the cells respond. Concerning printing geometrically, concerning what we do in synthetic structures, I would say you can print the most complex shapes with stereolithography very quickly. The issue is that it is only one material. So how do we program the geometry and the response for what we want without having access to multiple materials? The answer is to just print different porosities, something akin to metamaterials.

MF: As you indicate, you are printing only with one material. But obviously that is not how nature works. Does one also think in the direction of heterogeneous architecture? Different materials are combined with each other, with each material having a different function.

RS: This is something that does happen now, but not at the level of sophistication needed. We are working on a project right now where we are embedding carbon nanotubes into elastic structures to give us a particular stress response. But it is clear that this is not even near to the level of biology.

There is an opportunity here, though, to merge your other notion with this one. Printing a hard structure and nucleating the polymerization and growth of a soft one off of it for endoskeletal–soft tissue constructs (or, perhaps more difficult, the inverse).

MF: The question therefore may be whether and how we have to follow biological structures or be inspired by nature. In one of your papers you note that nature has a variety of ways to demonstrate these stretchable structures, whereas we only have the ability to inflate a balloon [Pikul et al. 2017] (see also Fig. 4). What can we actually learn from nature in respect to these stretchable materials?

Fig. 4: Design and displacement of axisymmetric membranes with positive, zero, and negative Gaussian curvature target shapes. The radial mesh patterns mapped from the composite radial strain. Black represents mesh, and gray is silicone. The resulting inflated shapes and Gaussian curvatures are shown below the mesh patterns. From: [Pikul et al. 2017, p. 2, fig. 2b]. Reprinted with permission from AAAS.

RS: Nature is very good at not making the best of anything but does adapt to lots of situations. Nature is always dealing with compromises. One way to get a good compromise is in mechanical compliance. Leaves want to absorb as much light as possible. They should be very broad, very thin, because all the light is absorbed in the first few layers. So why even be thick? In addition, when it is very windy, if they were rigid and fixed to a branch, the whole tree would fall down. How nature deals with that is by making the leaf actually fold up. The aerodynamic profile is greatly reduced. That is a very simple example of how compliance is used in nature as an engineering compromise. That is what bioinspiration is: seeing what nature is using compliance for.

MF: That points to one of the essential topics of the research on active materials. We program or manufacture materials that blur the line between the natural and the artificial, between biological and human materials. How does the community of scientists redefine essential concepts for these two domains, concepts such as ‘life’ or ‘intelligence,’ if for example the concept of self-healing is now blurred?

RS: As you point out, the problem here is defining what words may mean. Scientists have been ‘hijacking’ language. But, to speak more concretely, do we have a robot that can self-heal like a gecko? No. If you pull the tail off of a gecko, it can grow another tail (morphogenesis). Mostly what we are talking about when we talk about self-healing is – when there is a fracture the two surfaces recombine. We (re)define the word to capture that. But in nature, self-healing usually means regrowing. There are very few, if any, examples of that in soft robotics.

MF: Can one say that the current research points at least toward a change of the definition of ‘intelligence’? That intelligence is not necessarily connected to human beings.

RS: So maybe a Turing test for mechanics? Certainly there is a material computation which is intelligent: intelligently programming your material to respond to stress input.

KK: In the second half of the twentieth century, there was an emphasis on genetic biology and the expectation that it would be able to decipher and later even to (re)write the code of life [Kay 2000]. Obviously, these great expectations were not fully met. However, the 3D printing of living cells reminds me of this idea of reading and/or writing life. Hence, on the one hand, we are still thinking with our old concepts, but on the other hand there maybe also a new element that comes from robotics, namely that intelligence is not something related only to human beings or to animals, that intelligence is something that comes from diversity, from a play between forces.

RS: You have a point there – though I think that on an individual level we would not be able to do anything other than mimic biology. I also think that CRISPR is perhaps an example that shows we have kept up with our potential in working purely

within biology. But perhaps as a group something could emerge that is non-biometric. AI has a good chance of producing something non-biomimetic.

MF: To finish I would like to discuss again in more detail the example of the biomimetic robot you mentioned at the beginning of the interview. When we are talking about bodies of machines – for example, the soft locomotive robots or the quadrupedal soft robots you have developed (see Fig. 1) – this does not look like any animal or at least like any human being – and one may very well say that it walks in a way that is unpredictable. Can we manufacture materials that can act in unpredictable ways? Was the quadruped's way of crawling and walking predictable beforehand?

RS: I predicted that it could move. But after I made it I had to figure out the best way to make it move. I developed the gait after we had the body.

MF: Were you able to predict how it would move?

RS: In a very general sense. We knew that with the four legs of the quadruped, we would have to use some of them for stability but others for moving forward. We knew that if we made the angle between the legs and the body 90° it would not move forward, it would move sideways. If we made them just straight ahead, then we felt turning would be harder to do. It could have been 45° . But the exact angle between 0° and 90° is just a guess.

MF: By designing some legs to be stiffer, for example, does not one already preprogram a state of equilibrium? If all the legs would have the same functions, the same stiffness, and properties, one could say that it is in an equilibrium state. And not only that but that it would hardly move in that state.

RS: The question is: what does it mean to be out of equilibrium? I myself am out of equilibrium. If I take the legs away from the quadruped, it is going to be on the ground. Now it is clearly to be found more in a lower energy state but it can get even lower, since I could even burn it and it would release energy. So, when one says that something is out of equilibrium, the question is: relative to what? 'Out of equilibrium' may mean a highly dissipative structure; that is, one can put energy into it and that energy is going to be used to overcome some kind of energy barrier to ultimately lower the energy of the structure. Then there is a cascading effect of taking energy in and redistributing it to make the whole system reach a more energetically favorable state.

When we apply this to the quadruped, it becomes more out of equilibrium when I pressurize it. By pressurizing it, I increase its energy levels, so when I relieve the pressure it wants to dissipate that energy. My point is that there are degrees of how out of equilibrium a system is. For example, we as humans are so out of equilibrium that it is almost impossible to believe that we exist. Our proteins are constantly moving around but our body temperature stays the same. Every part of us at every level is just constantly in motion. It is amazing that we live as long as we do, or that we even exist.

Bibliography

- Aubin CA, Choudhury S, Jerch R, Archer LA, Pikul JH, Shepherd RF. Electrolytic Vascular Systems for Energy-Dense Robots. *Nature* 2019, 571, 51–57, DOI: 10.1038/s41586-019-1313-1.
- Bekey GA. *Autonomous Robots: From Biological Inspiration to Implementation and Control*. Cambridge MA, MIT Press, 2005.
- Holmes D. Elasticity and Stability of Shape-Shifting Structures. *Current Opinion in Colloid & Interface Science* 2019, 40, 118–137, DOI: 10.1016/j.cocis.2019.02.008.
- Kay L. *Who Wrote the Book of Life? A History of the Genetic Code*. Stanford: Stanford University Press, 2000.
- Lewis Lab. The President and Fellows of Harvard College, 2021. (Accessed January 19, 2021, at <https://lewisgroup.seas.harvard.edu/>.)
- Mishra AK, Wallin TJ, Pan W, et al. Autonomic Perspiration in 3D-Printed Hydrogel Actuators. *Science Robotics* 2020, 5 (38), eaaz3918, DOI: 10.1126/scirobotics.aaz3918.
- Pikul JH, Li S, Bai H, Hanlon RH, Cohen I, Shepherd RF. Stretchable Surfaces with Programmable 3D Texture Morphing for Synthetic Camouflaging Skins. *Science* 2017, 358 (6360), 210–214, DOI: 10.1126/science.aan5627.
- Shepherd RF. Embodied Energy for Enduring Robots. ACM Symposium on Computational Fabrication. Lecture, June 17, 2019. (Accessed January 19, 2021, at <https://www.youtube.com/watch?v=eb8DH9yswql>.)
- Shepherd RF, Ilievski F, Choi W, et al. Multigait Soft Robot. *PNAS* 2011, 108 (51), 20400–20403, DOI: 10.1073/pnas.1116564108.
- Tolley MT, Shepherd RF, Mosadegh B, et al. A Resilient, Untethered Soft Robot. *Soft Robotics* 2014, 1 (3), 213–223, DOI: 10.1089/soro.2014.0008.
- Van Meerbeek IM, Mac Murray BC, Kim JW, et al. Morphing Metal and Elastomer Bicontinuous Foams for Reversible Stiffness, Shape Memory, and Self-Healing Soft Machines. *Advanced Materials* 2016, 28 (14), 2801–2806, DOI: 10.1002/adma.201505991.
- Wallin TJ, Pikul JH, Bodkhe S, et al. Click Chemistry Stereolithography for Soft Robots that Self-Heal. *J Mater Chem B* 2017, 5 (31), 6249–6255, DOI: 10.1039/C7TB01605K.

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Robert F. Shepherd is interested in developing disruptive manufacturing technologies (e.g., 3D printing, replica molding, and microfluidics) and functional materials to enable new devices and user experiences. He is particularly interested in simultaneously increasing the speed, dimensionality, resolution, and materials capability of free-form fabrication techniques, and developing soft actuators that mimic biological functions, but not necessarily their mechanisms: These interests are synergistic and will, perhaps, enable more efficient and life-like machines. His main research themes are energy-dense robots, engineered living materials, haptics and prosthetics, underwater robots, agricultural robots, and additive manufacturing.