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ROUNDTABLE DISCUSSION

3D Printing Soft Materials: What Is Possible?

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Participants: Jennifer A. Lewis,[2] Robert F. Shepherd,[3] and Hod Lipson[3]

Soft Robotics (Barry Trimmer): *Thank you, everybody, for joining us for this roundtable discussion. We are going to be talking about 3D printing soft materials. I think that this is the cutting edge of the technology, and is also likely to have quite important disruptive effects. So I would like to talk about the prospects, what is exciting about it, and some of the limitations. First, though, if you could perhaps tell us briefly how you are using 3D printing in your research.*

Hod Lipson: We are using 3D printing to make robots. We have been using it for almost two decades now, in various ways. We have been using it with conventional hard plastics, but more recently moving on to soft materials and to active materials, such as conductors, batteries, actuators, and so forth. We have also been exploring esoteric materials like biomaterials and even food.

Jennifer A. Lewis: We have also been working on 3D printing for over a decade, and our focus is to design new materials that enable the integration of form and function via 3D printing. Rather than simply printing complex shapes, we aim to print functional parts composed of soft or hard materials. We employ an extrusion-based 3D printing method and have used this method to fabricate a broad range of functional mechanical and biological architectures.

Robert F. Shepherd: We have primarily been 3D printing the negative of the form of a robot, and then casting materials into these negatives, and then bonding two halves together to form a complete robot. There are occasions when we want to have complex—more complex—functions, where we will directly 3D print the robot using a stereolithographic method. But the materials are quite limited, and we have to make some critical design choices to get the function we want. But if we had more materials choices, we can make better robots, and therefore we are designing materials compatible with stereolithographic printers for directly printing 3D robots.

Soft Robotics: *I am going to interject myself here, as a researcher instead of just the editor-in-chief, to say a little bit about our use of 3D printing, for soft robots. We are taking advantage of the fact that the robots we have been designing and building are monolithic structures. They do not work by inflation, by pneumatics, or by fluidics but instead use musclelike actuators, either shape memory alloy coils or motor tendons. And so that allows us to use the existing soft materials that can be 3D printed commercially. But they are limited. The material does not have all of the properties we would like. We cannot modify it in the ways we would like. So we are working within the constraints of the current technology.*

So that brings up the next area I would like to get your opinions on: What additional capability would you like to see incorporated into 3D printing?

Hod Lipson: If I look at the repertoire of materials that are necessary to make a robot, I can see a couple of places that are still missing. First, to put things in perspective, one of our goals in the lab is to print a complete robot that will walk out of the printer, batteries included.

Printing in structural materials—that's easy. Printing soft materials, that's been done many times. Even active materials—like conductors, batteries, and sensors—have already been printed in various ways. But one of the places that I think there is to fill in the gap is actually actuators—materials that move. Of course, actuators are critical to making any kind of robot, but there is no good solution at this time—it's very, very difficult to print. I think that is one gap that is still missing. And then, of course, integrating it all together, in one print job.

A second limitation, which is somewhat outside the materials space, is that of design tools. The ability to simulate and design printable objects is very developed for static, hard, rigid objects, but it is still far behind when it comes to soft materials and materials that are active, like actuators, sensors, and so forth.

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So I think these are the two gaps, actuator materials—that is on the hardware side—and simulation and design tools, on the software side.

Jennifer A. Lewis: I would echo Hod's comments on design tools. We are especially interested in the ability to integrate electrical wiring and components within CAD files. Autodesk is developing a software package called Project Wire that can route conductive wires, or any channel-like architecture, within any three-dimensional object. This is an area that I think will have a dramatic impact on 3D electronics, robotics, and wearable devices.

I would also like to see advances in true multimaterial printing. Many materials that we use do not flow through inkjet print heads. There are a lot of constraints on ink formulations that can be jetted by that approach. I would love to see individually addressable, multinozzle print heads be expanded to other printing platforms, such as extrusion-based printing of concentrated inks. We have made some progress there, but there is much more to do, and I think it would have a huge impact.

Robert F. Shepherd: I definitely agree with both Jennifer and Hod, and also would point out that one of the biggest missing parts to building a robot, which I think both Hod and Jennifer were alluding to, is the incorporation of digital logic into the prints, which both Jennifer and Hod have contributed a lot in that area, or provided capabilities that will contribute to that. And that is an exciting development.

Some practical issues that I think need to be solved are the speed at which these 3D printers produce objects, the reliability with which they produce them as well, and the ability to print with minimal support material, because even though we would like to print whatever we want, many times there are constraints, because we have to support freestanding objects. So these design considerations go into what we print in our labs, and especially what we mold in our labs. That has been more restrictive. So these obstacles are constantly an issue for us.

Jennifer A. Lewis: I would like to echo that. I think Rob has touched on some really key areas that are important not only for soft material printing, but also for any kind of 3D printing. Enhancing speed, reliability, and the ability to move away from support materials would be huge, huge.

Soft Robotics: *So that sounds like one of the common limitations of 3D printing is the lack of speed, and that it is not easily scalable. Is there a way around that? Is there a way that 3D printing can be used and scaled up to be much, much faster? You know, if you could have a million jets on each print head, I am guessing things would go a lot faster. But is that what you see as one of the limitations?*

Jennifer A. Lewis: The real goal of 3D printing should be to dramatically enhance the volume of material printed per unit time, while still maintaining (or improving) local compositional specificity and resolution. The ability to have many nozzles dispensing material controllably will help that problem quite a bit. Presently, inkjet print heads are the most advanced, because they have been used for 2D printing for a long time. However, if we want to work with a broader palette of materials, we do not have that analog for other 3D printing processes. They simply do not exist.

Hod Lipson: I have to say, though, just to disagree a little bit. I think that, in looking at robotics and 3D printing, speed probably is not the biggest limitation. None of us are yet at the point where we are mass-producing robots, where speed is a bottleneck. In fact, I would be happy if it worked at all, even if it would take a week. So really, being able to integrate all these different materials together into a single print job is what will allow us to take advantage of 3D printing complexity. Speed, reliability, efficiency, all these things come at a much later stage, I think, than where we are today.

Soft Robotics: *It seems to me that one of the fundamental problems of 3D printing a soft material is that it tends to deform under the forces that are normally being used, even during the build. So it will deform under its own weight, requiring a support material.*

Are there any ways around this, or is it simply going to need to wait for some miraculous materials that can be printed as rigid structures, and then allow it to be soft? Is there anything on the horizon that you think is like that, or is this going to be a limitation for all soft material printing?

Jennifer A. Lewis: Well, Rob, in his PhD work at my group, developed viscoelastic hydrogels that can be printed in span and self-supporting. So I will let Rob talk about some of the work that he has done there. We have recently extended this to elastomers and other soft materials in my lab here at Harvard.

Robert F. Shepherd: Yeah, so hydrogels can span from single kilopascal elastic moduli up to hundreds of kilopascals to even megapascals. So getting these very low elastic modulus hydrogels to span, we incorporated solvents, very viscous solvents that really limited the kinetics of the polymer diffusion, which allowed us to span gaps with these very soft materials. We would then use photopolymerization to impart long-term shape retention under significant loading.

But one thing I would like to say is that Jennifer actually developed an omnidirectional printing technique as well, which allows you to print extremely soft material (even liquids), inside of a yield stress fluid that you could choose to polymerize and hold in place or remove later.

Another thing that makes printing very soft material possible is photolithographic techniques. In these systems, you are printing in a resin bath, and that unreactive resin can also help to support these very soft materials from deflection. Of course, you still have to remove that resin, and depending on how you define your architecture, you probably have to link your very soft materials to very hard materials, which brings you to the problem mentioned earlier; it is very hard to print with multiple materials lithographically. So it is still an existing problem in that toolkit.

Hod Lipson: And of course, the age-old solution of support structures—structures to temporarily hold the parts together while you are printing, and that are removed later on.

Soft Robotics: *So that sounds like some of those limitations could actually be minimized a little bit by some of the alternative materials and approaches. It does not sound like it is hopeless, which is great. Do you think that it is possible for soft material printing to be done with positioning technology that* *can use multiple materials? Is that a direction that things are likely to go in, or are there just too many problems with that?*

Jennifer A. Lewis: Neri Oxman's group is doing 3D printing using a six-axis robotic arm.

Hod Lipson: Some of our work in 2006 used a six-axis robotic arm to do that. But we were not able to get the positioning accuracy that we could easily get with a simple gantry system. So it is conjecturally possible, but it just makes things a lot more complicated and expensive than necessary. So I think—let me put it this way—we have not reached that level of desperation yet.

We are still hoping that there is some magic single solution that will allow us to work with multiple materials without having to have this complex six-degree platform. But that is definitely a possibility.

Jennifer A. Lewis: I would just say, if you can avoid six-axis printing, it is better. However, if you are trying to do conformal 3D printing on an existing object, that is where the six-axis capability would really be very useful.

Hod Lipson: That is right. The six-axis system also allows you to print in a volume larger than the printer itself, and that is also very attractive.

Jennifer A. Lewis: Yes, that is a very good point, Hod.

Hod Lipson: But, Barry, what you suggested does not require a six-axis system. You could just have a gantry system with multiple print heads that are interchangeable, and that is definitely possible.

Soft Robotics: *Right. So I am interested in which direction you think some of this is going to go. Assuming that we can get a lot of different types of materials available for printing, what are the areas that you think this can have the biggest impact? I am particularly interested in whether you think that printing biomaterials or living cells is going to be transformative.*

Jennifer A. Lewis: I definitely think it is going to be transformative. However, I do not think that it will be transformative quite in the way that we all would hope, which is being able to reproduce very complex organ function.

But even for just printing architectures for drug screening, I believe that there are already companies doing that. But, secondly, I believe that there are more advances coming that will allow you to be quite sophisticated in creating human tissue mimics that can be used for drug screening that will provide a phase-zero trial that will kind of connect between, say, animal models that are used and human clinical trials. And so I think that is one very—sort of on the immediate-horizon area, where 3D printing of biological architectures will play a role.

Hod Lipson: I would echo that, and add one more area that I think is going to be even bigger. I know I am in the minority, but I think that future area is food printing—3D printing directly with food materials like chocolate, cheese, and cookie dough. Food printing involves soft materials, hard materials, certainly multiple materials. I think it's going to be a very large application space, and possibly the biggest. But again, there is a lot more work to do before we get there.

Soft Robotics: *That is a very interesting area, because I imagine that the entry barriers are quite low, you do not need tremendous precision, and it is an extension of the automation industry that we currently have to build food products. So I see your point on that.*

Rob, do you have any directions that you think are going to be particularly influenced by this sort of technology?

Robert F. Shepherd: Well, as somebody who does not really have the infrastructure to print cells, I am focused on synthetic muscle. And one really enabling piece of technology will be—would be printing at very high resolution, because muscle is a really complex system, natural muscle, and to try to mimic it synthetically, we really have to access hundreds of nanometers of resolution, and even then it is not true mimicry. But very high-resolution printing of synthetic soft materials, I think, will open up a lot of space in synthetic rather than biological physiology.

Soft Robotics: *I think one of the alternatives to printing tissues is to use the self-assembly capability of cells so that you do not need to actually build things. If we knew enough about the way to determine cells' fate and how they are assembled, then we can use that to get the cells to form tissues all by themselves. But that, of course, is tissue engineering rather than 3D printing. I think those two approaches are going to have different trajectories and different pros and cons. So it will be interesting to see.*

So I think we have covered quite a lot of ground. You have all been very, very helpful in explaining some of the directions of technologies. But are there other areas that we have not had a chance to talk about? Jennifer, I know you have been working on energy supplies. Are any of those actually available for soft material structures?

Jennifer A. Lewis: Well, we are in the process of completing another piece of work in that space with the aim of integrating power supplies into robots. But it is premature to say too much about that at this point.

Soft Robotics: *It is exciting to look forward to. That sounds very promising, so we will probably see that at a future date, I imagine.*

Jennifer A. Lewis: I hope so.

Soft Robotics: *Great. I think one of the leading problems, in addition to actuation for soft robots, of course, is power supplies. And most current technologies use very stiff materials in order to power the robots, and it would be lovely to have something maybe more liquid or soft that we could use. So, Hod, do you have any remaining comments or thoughts that you would like to share?*

Hod Lipson: I would like to just emphasize, again, the challenge of design tools and simulation tools. Our ability to model and understand and predict how all these soft materials work together is very, very important. And without them, we are sort of left with a trial-and-error design, and that is very slow.

So even though people tend to think about the materials and the hardware first, I think that simulation and modeling tools are going to be a big piece of our progress, and we have to find a way to make sure they keep pace with the hardware and material development.

Soft Robotics: *I completely agree. Rob, do you have any comments left, or things that we have not covered?*

Robert F. Shepherd: Sure. Well, this is more of just talking further about power sources for robots, which is a huge problem regardless of 3D printing. But with 3D printing, we have the opportunity to maybe more intelligently place power sources. And one area that I am not working on, but is probably an opportunity space, is printing these high-energy-dense materials like aluminum into structures. Aluminum has an energy density of about 30 megajoules per kilogram, so if you can incorporate that intelligently in your structure in a safe way, that could be a very powerful solution to energy storage in robots.

Soft Robotics: *That is a fascinating idea. I always thought that if we could print robots out of fat that they could consume themselves, and that would be a wonderful way to go. I think it is probably more practical, and it sounds like higher energy density to be using something like aluminum. That is a really interesting idea.*

I think you have all given some really, really interesting ideas and stimulating directions to go in. I think these soft technologies are going to be really extremely important for all future devices, whether they end up being soft or not. So thank you all for your time. I appreciate it.