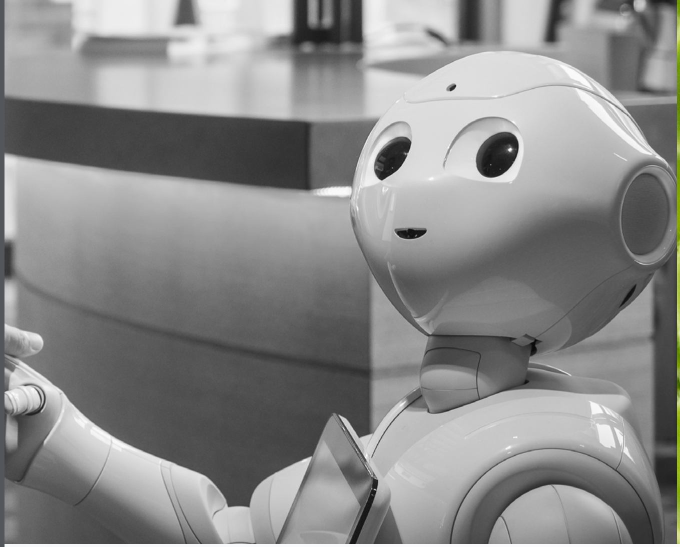
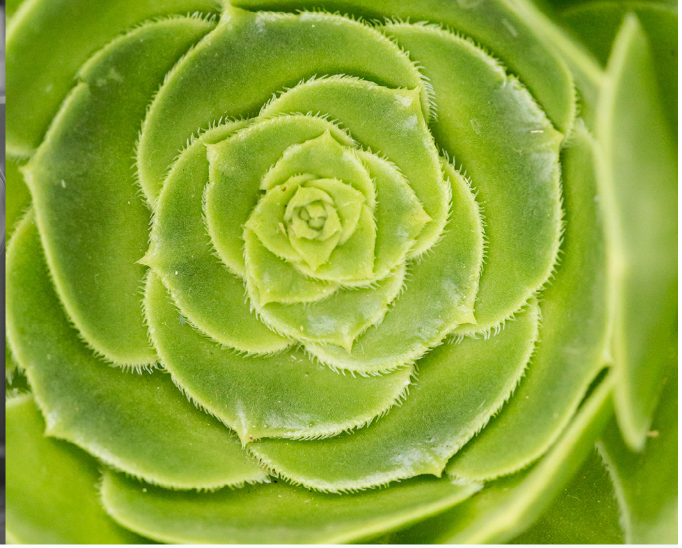




Robotics Inspiration Guide

3D Printing Your Way From Idea to Application

E-Book

Beyond the Movies

For many of us, our knowledge of robots comes from the movies. From R2-D2 to the Terminator, robots are viewed as friendly or sinister, something to be in awe of, or something to fear. They can be programmed to take on human acts but they never quite achieve the fluidity of human thought or movement.

What many of us may not realize is that the preponderance of robots today work in manufacturing facilities and bear little resemblance to those in the movies. Still, beginning with the first known robot around 400 BC, a bird constructed of wood and powered by steam, to today's highly-complex systems -- robotics is clearly here to stay.

Joseph Engelberger and George Devol created the first commercial, digital and programmable robot in 1954, and named him "Unimate." In 1961, General Motors bought Unimate, putting the robot on the factory floor to lift pieces of hot metal from die casting machines at the production facility.

Unimate was tasked with repetitive, difficult tasks not easily accomplished by humans, and this model has helped define robotics ever since. For nearly 40 years, robots and robotic appendages have successfully tackled dangerous, basic tasks, an industry estimated to hit $135.4 billion in 2019, according to International Data Corporation.

Robotic arms help assemble the cars we drive, pick the fruit we eat, and even assist in lifesaving surgery too precise to be accomplished any other way. Despite their rigidity, one of the reasons robots work so well for repetitive tasks is their ability to be analytically programmed to do simple tasks. One modern example of this is the robotic vacuum, Roomba, that circumnavigates your living room, systematically collecting stationary data points to use in future sweeps, accurately avoiding objects like chair legs.

Whether in the home or in industry, robots have played an important role in the past few decades but their capabilities and usage are poised for exponential growth thanks to a whole new category of robots arriving on the scene: soft robotics.

There is no one definition of soft robotics, but all definitions include a category of robots that are not only made from compliant material but have biomimetic capabilities, qualities which make them more readily adaptable to working alongside compliant beings (i.e., humans) and interacting with "soft" objects, such as produce, the human body, and even manufacturing materials. The growth of soft robotics is opening up myriad opportunities and adding tremendous value due to their increased application.

Soft Robotics: A Paradigm Shift

Fundamentally, soft robots are exactly what they sound like, robots that are compliant in places where it's most useful. And it's this softness that makes the new soft robots more successful interacting with everything from a strawberry to a human.

Constructing a robot from compliant materials, such as elastomers or stretchy plastics, gives them a far greater ability to interact with objects less rigid than they are. Scientists speak of "compliance matching" or the idea that "materials that come into contact with each other should share similar mechanical rigidity in order to evenly distribute internal load and minimize interfacial stress concentrations," according to Elveflow Plug & Play Microfluidics. Simply put, this means that

traditional robots, with their hard, rigid nature do not typically interact well with humans. Soft robots are both made with softer materials and are adaptable to equalizing their force relative to the object they are interacting with.

This extends beyond just the exterior casing of a robot. A problem with traditional robots is their inability to hold or grip or move objects less dense than they are. These robots either lack the ability to grip, or they grip so non-compliantly they crush whatever's in their grasp. For these reasons, hard robots lack the ability to interact effectively with real-world situations, whether it's packaging soft materials or interacting with humans in a medical scenario. Soft robotics, on the other hand, can interact more effectively and safely with humans, unknown objects and rough terrain – anything more compliant or non-linear.

In recent years, experts have fixed on three main advancements, enabling the rise of soft robotics: smart materials, mathematical modeling of compliant systems and fabrication technologies. The first two refer to advancements in either optics or mechanics, and the mathematical modeling that allows for nonlinear behaviors. For the sake of this paper, our focus will be on the third, new fabrication technologies that allow for the combination of hard and soft materials necessary for actuators, sensors and soft robotic casings.

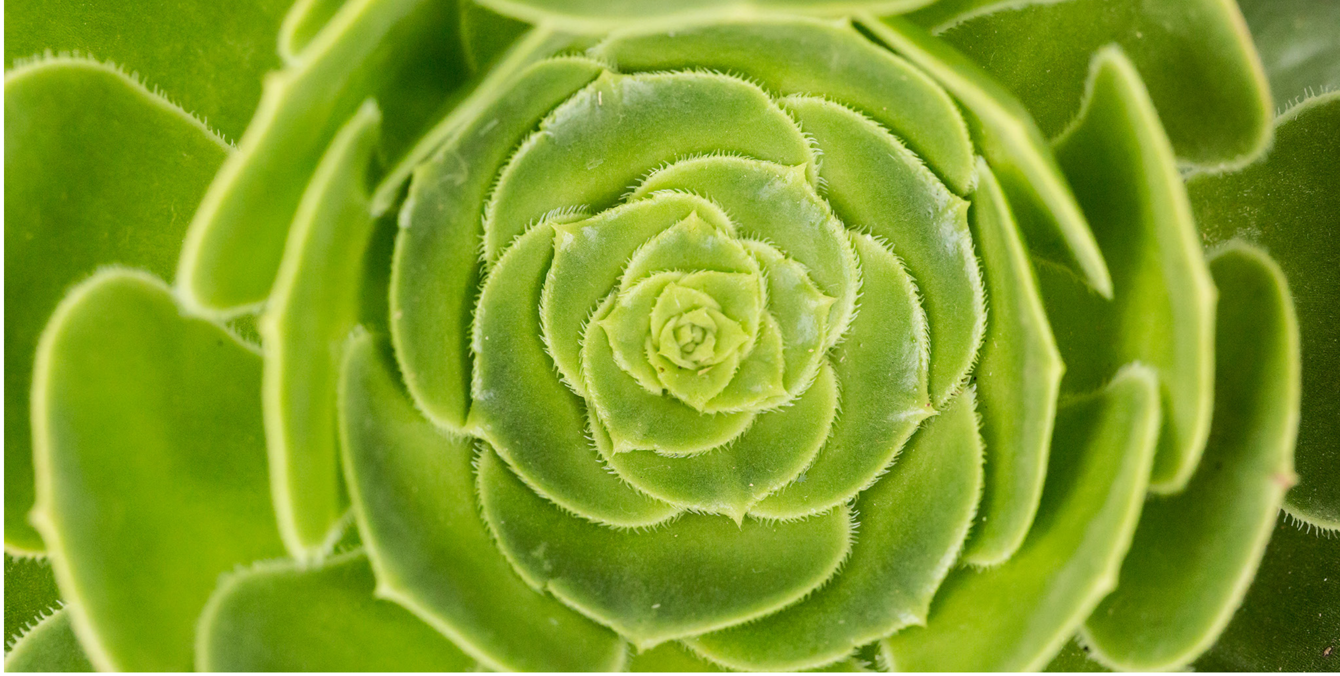
Nature as the Model for Soft Robotics

Biology itself seems to hold the answer to how to make robots more adaptable to their environment. As humans, when we step on a rock along a path we automatically respond to that change in our environment by compensating for that disruption. Our combination of a hard skeleton and soft tissue enables this fluidity of movement.

In the same way, animals and insects with exoskeletons, or external shells (or their bones on the outside of their bodies) but that have soft tissue beneath also have this innate adaptability. So, combining some robotic elements with the biomimetic traits found readily in nature has raised this study of “soft robotics,” or the ability to interact more effectively by adapting to changing situations the way nature does.

This not only opens up myriad use cases within production and industry but also means humans and robots can more safely interact in the same workspace. Contact between a robot and a human can have dire consequences; contact between a human and soft robot delivers a much softer landing.

“Biomimicry” is the study of mimicking the dynamics found in nature and producing them outside of nature. Organisms in nature have the ability to achieve smooth, fluid motion, such as earthworms, an octopus or an elephant’s trunk. This natural perfection, or adaptability to outside stimuli



“

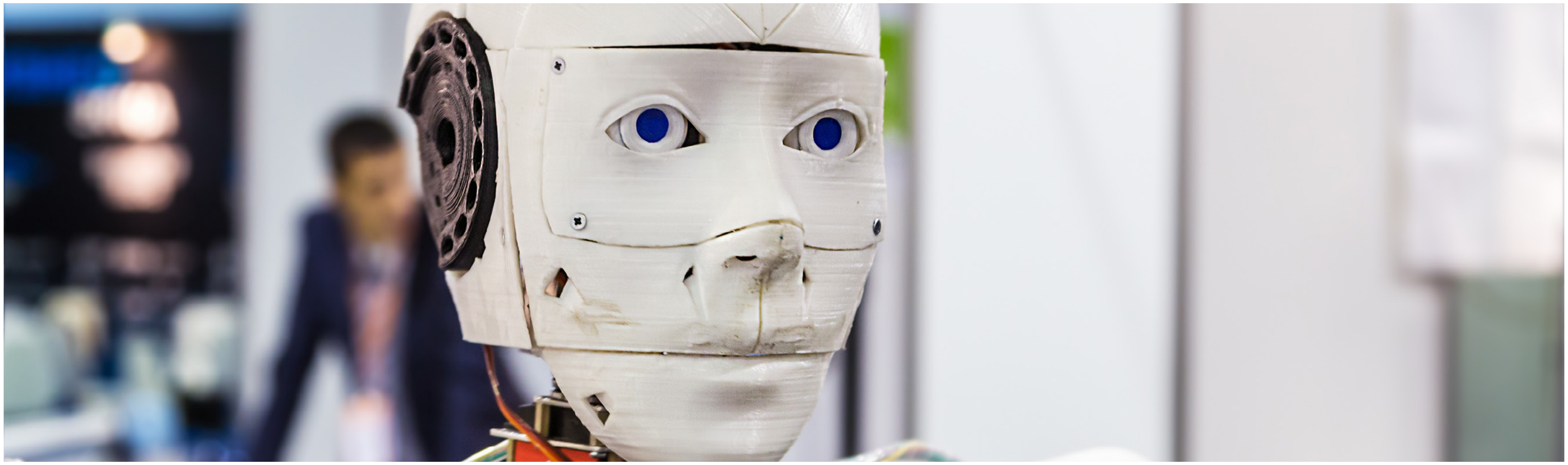
[The Creative Machines Lab is] interested in robots that create and are creative.”

Hod Lipson, Ph.D
Head of the Creative Machines Lab
Columbia University

is difficult to program. Robots are typically programmed with a confined set of parameters. Soft robots “adapt” to changing situations by way of unknown outside stimuli. Even plant cells respond to changes in the elements, producing hydrostatic pressure based on climactic forces. A plant’s shape and even its structure can change with pressure changes and this is a concept mimicked in soft robotics and used to devise pressure systems. This is only one such automatic instance in nature that the field of soft robotics is working to mimic.

Although endeavoring to mimic nature, soft robots still require one of three types of actuators to convert energy into motion. The first is pneumatics, explains Chloe Feast in “The Applications and Benefits of Soft Robotics,” University of Pittsburgh, Swanson School of Engineering, whereby air is pumped into compartments through micro channels that allow the compartments to expand and contract to form specific shapes. The second are actuators, says Swanson, which are able to produce bending patterns in pressurized fluid-filled chambers and the third is voltage, which mimics muscles that expand and contract in response to the voltage applied.

The goal is for soft robotics to be able to sense and respond to changes in their environment the same way humans, plants and animals can. To take it even a step further, these soft robots are being programmed to be able to bypass their “brain” or electrical data



center and respond organically to rough terrain or any other dynamic condition.

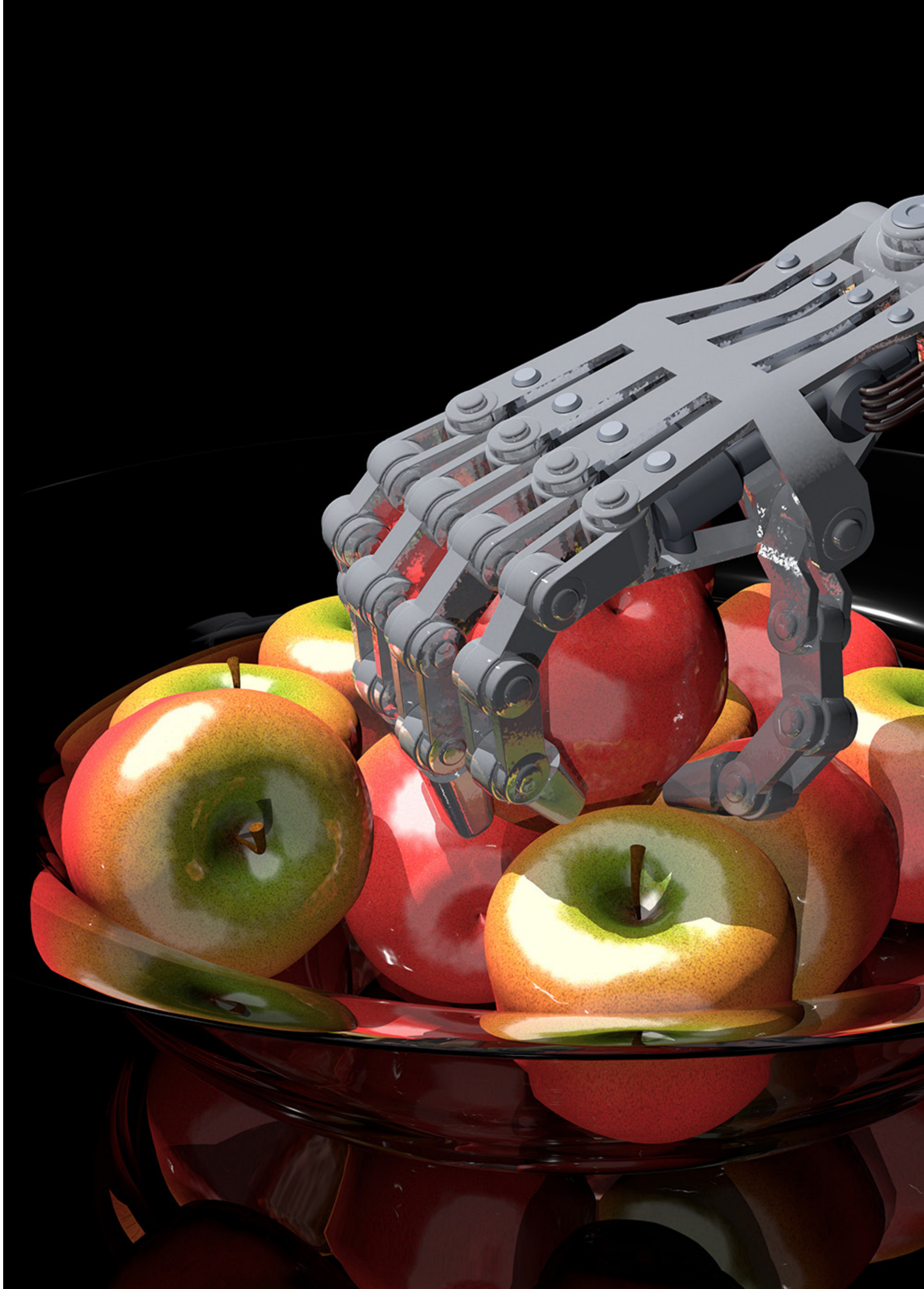
This capability of locomotion is why the field of soft robotics rose with advancements in materials and mathematical modeling before being viable. The third advancement – advanced materials combining hard and soft elements -- had been the final technological gap, until fairly recently. Even soft robots require embedded "muscles" and soft electronics to power their movement, something unattainable until recent material advancements.

An early entrant to the study of soft robotics is Hod Lipson, Ph.D, head of the Creative Machines Lab at Columbia University. The Creative Machines Lab is "interested in robots that create and are creative." Comprised of researchers from engineering, computer science, physics, math and biology, this team's work looks at "self-organization and evolutionary phenomena . . ." and is deeply "inspired from biology."

According to Lipson, his lab's work deals with "encoding" which is "essentially the blueprint of the design, analogous to DNA in biology . . ." which enables the "creation of more natural and life-like robots by trying to mimic nature and biology as much as possible."

Going Beyond the Automotive Factory Floor

So why all the attention to soft robotics? The potential applications for this adaptable technology have far-reaching implications in medicine, disaster recovery, warehouse and distribution, agriculture and more.



So why all the attention to soft robotics? The potential applications for this adaptable technology have farreaching implications in medicine, disaster recovery, warehouse and distribution, agriculture and more.

Robots were first used in the automotive industry and remain its largest use case today. In fact, estimates are that 75% of the automotive industry currently uses some form of automation with robotics. Much of this is still in rigid robotics but robotic usage is expected to skyrocket once systems are in place for soft robots that are capable of safe interaction with humans.

The beauty of soft robots is that the limiting factors of traditional robots do not exist in soft robotics, so the boundaries for their use can be pushed in new directions. Soft robotics can be safely used sideby-side with humans in an operating room or on a factory floor. From shapeshifting robotic implants that deliver laser-activated drug delivery to patients, to the rehabilitation of stroke victims through the use of a soft robotic glove to restore patient dexterity, to robotic-assisted surgeries that allow for precision and even shapeshifting (to reach difficult areas of a patient's anatomy), the uses in biomedical are astounding.

Risky tumor removal that requires extraction of a tumor and the affected surrounding tissue – but not the healthy tissue right up against it -- is aided by the precision of a programmable robot. MRI scans can pinpoint tumor locations and transmit them to the robot. This means more preceise extraction of the tumor and affected tissue.

Search and rescue missions can deploy soft robots to cover challenging environmental conditions to reach a victim and interact safely with the human, once there.

No less important to produce growers is a soft robot's ability to pick, handle and package delicate fruit in a way that doesn't decrease its market value through bruising and rough handling. This means fruit growers who struggle to employ enough workers to harvest their crops have a whole new tool. This directly speaks to the development of soft robotics with the ability to pick some of $13 million estimated fruit and vegetables wasted in 2015, due to the lack of pickers. This also extends to the packaging of frozen food items, a very difficult job to fill due to the environmental extremes a worker is subjected to.

Still, despite all the advanced in soft robotics, innovation and development are still in the early stages. Research facilities are busy tackling some of the most vexing problems still associated with maximizing the efficacy of soft robotics, such as: actuators, the pinching mechanisms and the materials used which enable both soft and hard combinations.

In the meantime, here are a couple of robotics applications in industry and manufacturing that despite their rigidity, still have broad application.

End-of-Arm-Tooling

Genesis Systems Group, a manufacturer of robotic work cells for welding, inspections and material processing, uses 3D printed end-of-arm-tooling (EOAT), to help increase efficiency and accuracy for a wide range of assembly and gripping functions. These EOATs are the essential "hands" of robotic machines that do the work of grasping,

Genesis used 3D printing to fabricate end-of-arm-tooling fixtures.

“

[The Robotic Composite] enables a whole list of vertical integrations that haven’t been possible until now . . . ”

Roger Hart
R&D engineering manager
Siemens

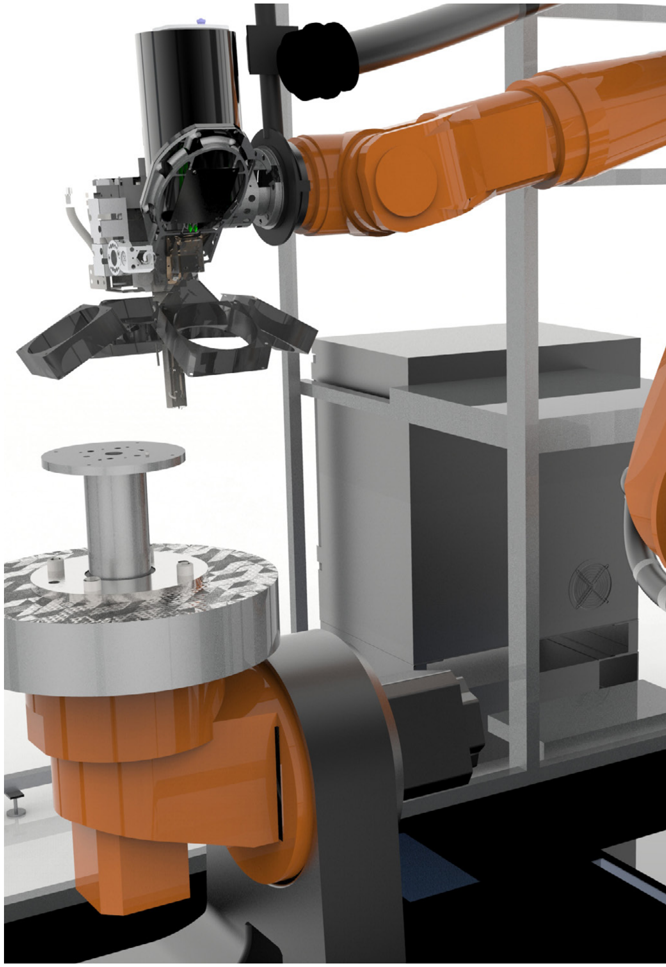
pushing and moving, which makes them indispensable parts for this manufacturing technology.

However, although EOATs make quick work of repetitive tasks, they are far from easily designed or produced. The multiple iterations necessary to make an EOAT fully functional mean they quickly become costly. Again, 3D printed EOATs made from sturdy FDM technology offer a costeffective and efficient alternative to traditional manufacturing methods. Easily customizable, these EOATs are capable of incorporating unique features like integral vacuum channels that are difficult to produce on metal tools.

The Stratasys Robotic Composite 3D Demonstrator

The Stratasys Robotic Composite 3D Demonstrator provides eight-axis freedom, freeing manufacturers from the layer-bylayer approach of previous additive technologies which limits composites production. The Robotic Composite enables precise material placement which maximizes part strength as well as build speed. Another plus is that no support material is necessary with this system, so post-processing and labor and lead time are significantly reduced.

“[The Robotic Composite] enables a whole list of vertical integrations that haven’t been possible until now, from material feeders to automation equipment to robot loaders and unloaders. We can now span the whole vertical automation framework that is necessary in factories,” said Roger Hart, R&D engineering manager, Siemens.



Bioinspired Robotics and Design Lab: UC San Diego

A quadruped 3D printed pneumatically controlled robot.
Photo courtesy of Bioinspired Robotics Lab, UC San Diego.

The University of California, San Diego's Bioinspired Robotics and Design Lab, part of the contextual Robotics Institute, tackles advancing soft robotics issues on a daily basis, in an effort to better advance soft gripper mechanisms, haptic object visualization, soft actuators, untethered quadrupeds, and origami folding fabrication.Gecko-inspired adhesive grippers:

“

[Our results] have the potential to increase physical safety in human-robot interaction . . . ”

Mike Tolley, Ph.D
UC San Diego’s Bioinspired Robotics and Design Lab

The importance and the challenge of a gripping mechanism that’s both compliant and receptive cannot be understated. Mike Tolley, Ph.D, leads the UC San Diego’s Bioinspired Robotics and Design Lab, and tests elastomer actuators for the gripping surface of robots powered by internal fluid pressure. Tolley mimics the gecko’s toe behavior to achieve high strength grasps with nearinstant actuation for both large and small objects. The trick here is that the fluid actuators enable an even gripping pressure across the structure so that an object can be uniformly grasped.

Soft robotic gripper sensor skins for haptic object visualization:

Adapting to changing or uncertain environments is a problem for robots. Tolley and his team have been studying sensors capable of recognizing complex motions. “We present sensor skins that enable haptic object visualization when integrated on a soft robotic gripper that can twist an object,” said Tolley.

His team assembles what amount to robotic “fingers” that can be inflated independently “to achieve a range of complex motions. Three fingers are combined to form a soft robotic gripper.” Through a complex system of 2D and 3D analytical models, Tolley is able to measure deformation and contact. Their results are approaching soft robot grippers capable of a complex range of motions and proprioception, “which will help future robots better understand the environments with which they interact, and have the potential to increase physical safety in human-robot interaction,” said Tolley.

3D printed soft fluidic actuators

Fluid is known to be one of the best compliance substances and Tolley and his team are working with fluidically actuated soft robots in unknown environmental conditions. Typically, fluidic actuators are inefficient, expensive and/or prone to leaks. The Robotics and Design Lab has devised a way to use not only pressure or vacuum as a means of actuation but also differential press actuation. The technological advancements in 3D printing materials allow Tolley’s team to 3D print soft robotic modules.

3D printed soft actuators for a legged robot on unstructured terrain

“Soft robots deform continuously along their bodies as opposed to only at discrete joints like traditional rigid robots,” said Tolley. Employing multi-material 3D printing for a robot powered by pressurized air, this robot with its multiple legs is able to locomote across a variety of terrain. This type of soft robot is particularly well-suited to being deployed in search-and-rescue operations.

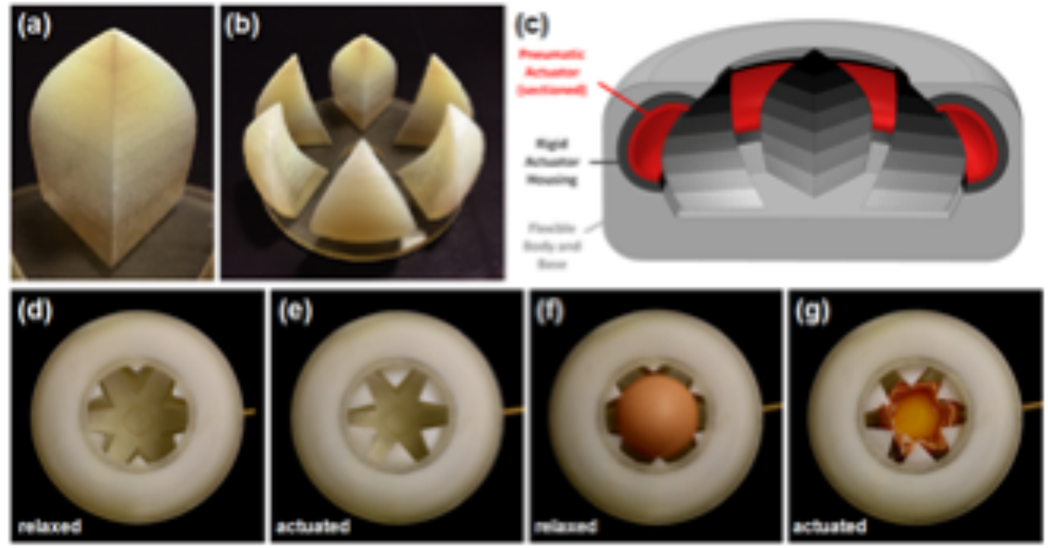
Soft robotic glove for kinesthetic haptic feedback in virtual reality

Sensory feedback is vital in the virtual reality world. Current versions of robotic gloves are rigid, which aren’t conducive to interactivity. Tolley’s team is working on a wearable soft robotic glove that can actually apply force to the fingers of the user. “The result is a haptic glove that is compliant, compact and unintimidating,” said Tolley.

Origami-style robots

Tolley’s team is also working with untethered quadruped soft robots and fabrication by folding, or origami-style soft robotics, drawing from nature again but until recently, lacking the material and fabrication capabilities now available to them through the use of multi-material 3D printing.

Challenges of **Robotic Gripping Mechanisms**



Pneumatic actuator 3D printed in multi-materials at UC Santa Barbara.
Photo courtesy of Bioinspired Robotics and Design Lab, UC San Diego.

Gripping mechanisms pose one of the greatest challenges to robotics designers. In an effort to mimic the complex gripping mechanisms found in nature, from claws to teeth, researchers have again turned to 3D printing to prototype these hybrid end effectors.

In their paper, “A Biologically Inspired, Functionally Graded End Effector for Soft Robotics Applications,” published in Soft Robotics magazine, researchers at UC San Diego found 3D printed prototypes offer “the potential for seamless fabrication of composite structures with complex architectures . . .”

3D printing in multi-materials provides this seamless integration not achievable by the assembly of various components. “The Connex3™ from Stratasys enabled us to 3D print an endofactor, kind of a gripper but looks more like a squid sucker, with teeth. These rigid teeth within a soft body could be 3D printed,” said Tolley.

Cutting-Edge Research into Soft Robotics Applications

There is a nearly limitless set of world applications for soft robots because they are able to safely interact with humans in close proximity.

Agriculture

There is a nearly limitless set of world applications for soft robots because they are able to safely interact with humans in close proximity. The Design Lab at UC San Diego is partnering with the California Strawberry Commission to develop soft manipulators for picking and handling the delicate fruit.

Michael Tolley and his team designed a graduate-level soft robotics course around gaining experience and solving challenges in strawberry picking and farming. The course description highlights the difficulty of "a one-size-fits-all device due to variations in size, texture and orientation. . ." and "When it comes to a robot with picking and manipulating fruit, some advantages of soft robots are their ability to conform to and interact with unknown environments."

The course brings together engineers and farmers to explore soft robotic solutions for picking and handling of the delicate fruit. Project-based, interactive, and hands on, course developers are advising students to "fail early and fail often to maximize their overall success."

Agricultural uses for soft robots also have incredible potential for improving picking efficiency and quality and alleviating worker shortages during prime growing seasons. The apple industry in states like Washington are so hopeful robotic pickers will stem the worker shortage they are investing heavily in complete orchard redesigns using dwarf varieties to help norm the picking process and make it more conducive to robotic pickers. One company, Soft Robotics Incorporated, has designed and built the Soft Robotics System which employs soft robotic grippers, a control system and software that can manipulate items of varying size, shape and weight with a single device. The company says "These end of arm tooling solutions enable industrial applications that previously were off limits to automation."

Defense

UC San Diego researchers are also working with the Office of Naval Research for soft underwater robots that can mimic the success of organisms like starfish. This project focuses on distributed actuation, sensing and control for soft robots. Starfish are able to coordinate thousands of tiny tubes to "achieve versatile feats of locomotion and manipulation (e.g., crawling on a rough sea floor and pulling bits of food toward their mouths), despite a relatively simple nervous system." The goal is their research is to design soft underwater robots that can replicate these abilities.

Medical

Robots are already in the operating room, facilitating surgeries dependent on precise movements only guaranteed by preprogrammed computer arms. Being sure to excise the exact measurements of a tumor without sacrificing any of the surrounding healthy tissue is one application.

The Harvard University Biodesign Lab is working with soft robotics to help alleviate the suffering of post-stroke survivors. They estimate there are approximately four million chronic stroke survivors in the U.S. alone, and "millions of others suffering from similar conditions." The result of stroke can often be loss or lessened use of hand motor ability and researchers at Harvard are "developing a modular, safe, portable, consumable, at-home hand rehabilitation and assistive device," according to Harvard's website.

In the same vein, researchers at Harvard estimate the lifetime risk of developing heart failure to be roughly 20% and current treatment of an implanted ventricular assist device has any number of risks associated with it. With soft robotics, researchers are working to develop a benchtop cardiac simulator and a Direct Cardiac Compression (DCC) device with soft actuators. This DCC would mean non-blood contact with the heart while still providing mechanical assistance during the phases of heart beat.

Conclusion

Historically, robots have had their place in manufacturing due to their ability to perform taxing, repetitive movements. But the future is soft robotics, with their added ability to not only perform repetitive tasks, such as fruit picking, but to do so with the haptic feedback required to deliver ripe, unbruised fruit.

Of course, as important as the agriculture industry is, the push for soft robotics does not stop there. From the operating room to the rescue site, soft robots are rapidly gaining the ability to work alongside their human counterparts in a safe way, navigate unknown terrain and fulfill their mission even in the midst of toxic conditions.

It's endlessly fascinating that nature itself provides the infinite model for the field of soft robotics. Time will tell how close human design can come to cracking and successfully mimicking the endless codes found in nature.

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