https://doi.org/10.1038/s44222-023-00126-5

Robots may transform the way we produce and prepare food

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Robotics technologies are finding their way into the food production chain, from agriculture robots 'working' on farms, to 3D food printers generating customized dishes in the kitchen. In this Viewpoint, two roboticists, Hod Lipson and Salah Sukkarieh, discuss the possible roles of robotics in shaping the future of food, highlighting how robots may be able to produce more, healthier and sustainable foods with fewer resources and a lower carbon footprint.

How could robotics shape the future of food?

Salah Sukkarieh: As we navigate the complexities of food production on farms, the need for innovation has never been more critical. In this context, the integration of real-time and automated precision agriculture through small electric robots emerges as a pivotal advance.

Agriculture robots are not just machines on farms[1]; they are intricate systems in which mobile electric platforms, sensor fusion and autonomous decision-making come together to create an unparalleled level of agricultural accuracy operating in real time.

The first layer of precision comes from the diverse array of sensors integrated into each robot. These can include soil moisture and nutrient sensors, as well as various external sensors such as multispectral and hyperspectral cameras, radar, vision and light detection and ranging. Each sensor has a specific purpose, and when the data streams are fused, the robot gains a comprehensive understanding of its environment, both below and above ground. For example, soil moisture sensors can provide data on water beneath the ground, and combining this data with prediction algorithms on crop stress, based on sensing from the robot from above the ground, the timing and quantity of irrigation can be optimized. Similarly, multispectral cameras can identify nutrient deficiencies in plants, allowing the robot to apply fertilisers selectively down to the individual plant level[2]. This level of customization ensures that the actions of the robot are tailored to the specific needs of each plot, each plant, even down to each square millimetre of soil.

The second layer of precision lies in the ability of the robot to make real-time decisions based on sensor data. Agricultural roboticists have developed methodologies and processes to design robot sensing systems that can identify a specific type of weed growing near a crop, and onboard decision algorithms can then determine the most effective herbicide for that weed and instruct a precision spray system to pinpoint and micro-dose the weed, thus minimizing the use of chemicals. Alternative approaches also examine how precision mechatronic tools can mechanically remove a weed with minimal soil disturbance and hence not use chemicals at all.

Hod Lipson: Robots are transforming manufacturing processes across almost every industry sector, from automotive to medical production. Since each of our home kitchens is essentially a small manufacturing plant, these could be next in line to be transformed. Most of us still cook using the same techniques and processes our ancestors have used for millennia: we wield sharp knives, mix bowls of ingredients and sear over an open flame. There has been less innovation in the technology of cooking, compared to technological progress in other fields.

Most people imagine robots in the kitchen as shiny humanoids flipping burgers or chopping salads. However, such a human-centred view of food-robotics might overlook broader opportunities that go beyond just automating our current way of preparing foods, and instead, open up an entirely new way of thinking about personal food preparation and even rethinking food itself altogether. The challenge is how robotics could affect food production at home rather than production in factories, where automation is already prevalent.

One fascinating example of robotics in the personal kitchen is the food 3D printer. Food printers, first introduced in 2007 (ref. 3), deposit precise amounts of basic ingredients according to a digital blueprint to create a 3D food construct[4]. The raw ingredients include frozen cartridges containing printable liquids, gels, pastes and powders, such as water, olive oil, ground salmon or shredded cheese[5]. When combined with new software-controlled cooking techniques such as precision lasers[6], 3D printers can deposit and cook ingredients simultaneously to create ready-to-eat dishes on demand. But just as an inkjet printer can create a huge range of shades of colour, not by mixing paints, but by dithering primary inks into complex patterns, food printers could potentially create a huge repertoire of new flavours, textures and nutrients, some of which are impractical using manual bulk cooking techniques.

Where do you see the greatest benefits of robotics regarding food demand and sustainability?

Salah Sukkarieh: The electric nature of agricultural robots is a deliberate design choice aimed at reducing the carbon footprint of farming operations. Traditional internal combustion engines used in agricultural machinery are notorious for their greenhouse gas emissions. By contrast, small agriculture robots are electrically powered, offering a cleaner, more eco-friendly alternative. Moreover, these robots can be integrated with solar panels, further minimizing their environmental impact and, in some cases, able to perform whole-day operations. The goal is not just to replace internal combustion engines but also to redefine the energy infrastructure of agriculture itself. The small size of these robots also means that they require less energy for movement, and their precision targeting means that tools are activated only when needed, thus minimizing energy use.

Beyond the electric power source, the robots are equipped with advanced path planning and control algorithms, designed to optimize energy use. These algorithms monitor the robot's operational parameters in real time, adjusting them to ensure that the robot functions at peak energy efficiency[7,8]. For example, if the robot performs a task that

does not require maximum motor torque, the algorithms reduce the power output in real time, conserving energy. This level of energy optimization is not an add-on; it is a core component of the system architecture, designed to make the operations of the robot as sustainable as the agriculture it supports. Other examples include optimized paths around the farm that the robot follows to minimize energy draw.

As the global population continues to grow, the demand for food is expected to increase substantially, posing a substantial challenge to current agricultural practices. Traditional machinery methods may struggle to meet this demand without causing further environmental degradation. This is where the role of small agricultural robots becomes even more critical. By combining real-time data analytics with precision application of resources on a small platform footprint, these robots can increase crop yields and minimize waste and environmental impact. Their ability to perform targeted actions, such as precise weeding, optimized planting and judicious use of fertilizers, ensures that each square millimetre of farmland is used to its maximum potential. Their light weight can also help to minimize soil compaction. These robots offer a way to meet growing food demand without compromising sustainability. They provide a scalable solution that can adapt to varying agricultural needs and produce more food with fewer resources.

Hod Lipson: It is sometimes said that when it comes to food, you can have health, convenience and low-cost — choose any two. Food that is healthy and low-cost requires effort, time and skill to prepare. Food that is cheap and convenient is not necessarily healthy. And food that is healthy and convenient, such as that prepared by a personal chef, is not cheap. Some have attributed many contemporary maladies to poor nutritional and eating habits, and most of these can be traced back to the skill, time, effort and attention required to make nutritious and affordable meals consistently. Everyone wants to eat healthy food, but not everyone has the time, money or skill. Bringing robotic automation into food preparation in the personal kitchen could help to break this cycle and open the door to processes that allow all three advantages simultaneously.

For many, the idea of a food printer conjures up images of an elaborate sausage-making machine creating new forms of Frankenfood, an image opposed to natural wholesomeness. But the reality is quite the contrary: a food printer loaded with natural raw 'inks' of basic wholesome ingredients, such as water, salt, organic garlic paste and minced wild-caught tuna can create dishes on demand that are healthy, cheap and convenient; healthy, because it is freshly cooked on demand, cheap, because only the required raw ingredients are used; and convenient, because the dish is made automatically without requiring an investment of time, attention or effort.

Many of us are interested in improving our diet but translating the nutritionist's recommendations into practice is difficult. We come home with a list of nutritional goals, but when we open the refrigerator, we face the same old ingredients. The link between robotics and artificial intelligence could allow us to dial in our nutritional requirements and constraints, bridging the gap between nutrition theory and practice. Need less sodium and more protein, less sugar and more calcium? No problem — let the robot's software handle it. A 3D printer could be used to tailor food for a patient with dysphagia or to modify food for a keto diet. Overall, allowing users to experiment effortlessly and cheaply with healthier options could transform the way we all eat for the better[5].

Ultimately, allowing artificial intelligence tools to make subtle changes to our diet based on personal medical and genetic markers and data collected from biometrics could accelerate intended health outcomes and maintain personal choices. As artificial intelligence learns from anonymized data gathered from the taste preference and health responses of millions of users, optimal and customized food preparation strategies beyond the capabilities of even the most dedicated physician–nutritionist–chef could become commonplace.

One example of a promising application of food printing is the preparation of meat surrogates[9]. Plant-based synthetic meats have struggled to create textures that resemble cuts of real meat and have remained mostly in the form of patties because of this challenge. However, 3D printers allow for the assembly of basic plant ingredients and spices into 3D constructs that begin to look, taste and feel like a cut of real meat. This developing technology could eventually allow us to combine sustainable sources of proteins, such as plants, insects and lab-grown proteins, into far more appetizing and realistic forms than what can be done using manual techniques alone[10].

What about the costs of using robotics in food production?

Salah Sukkarieh: When evaluating the cost-effectiveness of any technology, especially one as transformative as agricultural robotics, it is essential to adopt a multi-faceted perspective. Although the initial capital expenditure is often the focal point of cost discussions, this narrow view fails to capture the full economic and environmental landscape in which these robots operate.

The upfront costs associated with acquiring these robots are indeed significant, but it is crucial to consider this as a long-term investment. Generally, agriculture robotic companies have found that using agriculture robots for high-labour intensive tasks provides a return on investment within two to three years. However, most companies are offering alternative business models. Many on-farm robotic solutions are provided as a service, thus removing the need for increased capital expenditure. Furthermore, the modular design of many agriculture robots allows for easy upgrades, extending their operational lifespan.

One of the most immediate returns on investment comes in the form of operational efficiency. Traditional farming methods often require a large workforce for planting, weeding[11–13] and harvesting tasks. Agriculture robots are designed to automate these labour-intensive activities, considerably reducing the need for manual labour. This cuts

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Hod Lipson has been a professor of Engineering and Data Science at Columbia University in New York since 2015 before which he spent 14 years as a professor at Cornell University. He received his PhD in 1999 from the Technion–Israel Institute of Technology, followed by a postdoctorate at Brandeis University and MIT. Hod Lipson's work on self-aware and self-replicating robots challenges conventional views of robotics and has enjoyed widespread impact. He has also pioneered open-source 3D printing, as well as electronics 3D printing, bio-printing and food printing.

down on labour costs and allows more consistent and precise execution of tasks, leading to higher crop yields and, consequently, increased revenue.

Another often-overlooked aspect of cost-effectiveness is the environmental impact of agricultural practices. Traditional methods come with hidden costs, such as soil erosion, excess chemical use and the carbon footprint of gas-, fuel- or oil-powered machinery. By minimizing these environmental externalities, electrical and precision-based agriculture robots offer another form of cost-effectiveness. Their ability to apply resources, such as herbicides and fertilisers, in a targeted manner reduces waste and minimizes environmental degradation, effectively lowering the 'true cost' of farming.

Furthermore, adopting robotic agriculture can stimulate economic growth in related sectors, such as renewable energy, sensor manufacturing and data analytics. This creates a ripple effect that extends the economic benefits beyond the individual farm or robot, contributing to a more sustainable and resilient agricultural ecosystem.

Hod Lipson: Food printing is not inherently cost-effective compared to mass production of food. It is slow, energetically quite inefficient, and rather expensive when measured by the pound. We once approached a colleague in nutritional sciences with our cookie-printing machine. When he asked how many cookies we could print per second, we had to admit that the number was in the fractions of a per cent. But what food printing lacks in speed, energetic efficiency and cost-effectiveness, it can compensate with scope, variety and nutrition[14].

In conventional 3D printing with materials, such as polymers and metals, the immediate printing costs are often compensated by the long-term savings afforded by the printed product itself. For example, 3D printing an optimized aircraft component might be more expensive in the short term than milling the part out of a solid block. However, the weight savings gained by the geometric freedom enabled by 3D printing save fuel and emissions over the lifetime of the aircraft to an extent that far outweighs the initial cost investment. Similarly, although printing a meal could be more expensive than mass production pound per pound, both in terms of time and energy, the cost savings afforded by healthier composition[15], larger variety, less waste and more freshness may well be worth the wait. Such calculations underlie the growing interest by the National Aeronautics and Space Administration (NASA) in food printing for space travel[16]. Space travellers on long missions, such as on extended stays aboard the space station or a lunar colony, crave variety, health and freshness, while time and energy may be plentiful.

How accessible are robotics technologies to communities in resource-limited settings?

Salah Sukkarieh: In the context of agricultural robotics, it is not just about making advanced technology accessible to large, well funded farming operations but also about reaching out to make the technology accessible to smallholder farmers[17,18].

One of the most compelling aspects of small electric agriculture robotic technology is its inherent scalability[19]. Whereas the robots deployed in large-scale farming operations may be equipped with an extensive array of sensors and capabilities, the core functionalities, such as precision planting, targeted weeding and resource optimization, can be retained in scaled-down versions. This design approach allows the creation of models more affordable by smallholder farmers without compromising on the essential features.

The modular design of agriculture robots allows for customization to meet the specific needs of different agricultural settings and can be tailored to local conditions. This adaptability ensures that the benefits of robotic agriculture are not confined to a one-size-fits-all model but are accessible and relevant to diverse farming communities. Furthermore, the impact of open source becomes even more profound in agriculture robotics. By making the design schematics and codebase of these robots publicly accessible, we can invite a global community of developers, engineers and farmers to contribute to and refine the technology. This collective intelligence approach accelerates innovation, as solutions to challenges are crowdsourced from diverse perspectives and expertise. Moreover, open source ensures that the technology remains adaptable and customizable, allowing local communities to tailor the robots to their specific needs without proprietary constraints. Additionally, it democratizes access, ensuring that smallholder farmers, or those in low-resource settings, can benefit from the latest advances without prohibitive licensing costs.

The road to truly democratized agriculture robotics is not without its challenges. It requires supportive policies, public–private partnerships and educational initiatives to facilitate the adoption of this technology across diverse settings.

Hod Lipson: Although robotics in the kitchen seems expensive and far-fetched today, so did smartphones not so long ago. Yet today, the vast majority of people own smartphones, with the technology allowing them to accelerate access to education, healthcare, financial security and many other services.

Access to personal robotic food preparation appliances could follow a similar path, where early adopters will create a market that would eventually lead to many downstream consequences, such as healthier eating, less waste and faster innovation cycles in the food space, compared to conventional methods of food preparation.

What would it take for food printers to become a commercial reality? Food printing technology and laser cooking are relatively 'low-tech'. The barriers to their adoption are not technological, but social and economic; that is, the lack of the comprehensive ecosystem of printers, recipes and ingredients that are needed for a thriving and economically viable marketplace.

Do you think robots may be able to replace humans in the food production chain?

Salah Sukkarieh: Automation in agriculture will see the same effect as in other industries. Although agriculture robotics may replace on-farm labour-intensive tasks, it will also mark a transformative shift in the roles that humans have in the agricultural ecosystem, redefining their roles as skilled stewards and decision-makers.

Agriculture robots and humans will have a complementary role. On the one hand, agriculture robots will excel at on-farm repetitive, labour-intensive tasks that require precision and consistency, such as planting seeds at exact depths or applying fertilizers in precise quantities. On the other hand, farmers, agronomists and agriculture land stewards will bring complex problem-solving abilities, the capacity for strategic planning and the ability to fuse the whole of the supply chain into their operational thinking. Thus, agriculture robots will serve as an extension of human capabilities.

This shift will also probably lead to the creation of new job categories, such as agricultural data analysts, robot maintenance technicians and precision farming specialists. Thus, robotic agriculture has the potential to transform unskilled labour into skilled

labour, offering avenues for career growth and development.

The ethical and social implications are also equally important. The transition to robotic agriculture must be managed carefully to ensure it does not exacerbate social inequalities or lead to widespread job displacement. Training programmes, educational initiatives and policy measures will be essential in preparing the existing workforce for the changes ahead, ensuring that the benefits of automation are equitably distributed. This should probably start in secondary schools and transition to technical colleges and universities. The teaching and training of this technology may lead to an increased desire for the younger generation to work in agriculture.

Hod Lipson: Robotic food preparation, in any form, is not a replacement for human-prepared food. Just as microwave ovens did not replace the frying pan, food printers and laser cookers will probably become yet another appliance in our kitchen that will augment the range and scope of what we can make in the kitchen, not limit it.

Food printing and other forms of robotic automation in personal food preparation could increase access to a large variety of food styles and cuisines by facilitating recipe sharing and experimentation. These experiences would ultimately increase our interest in foods, expand our palates and make 'live cooking' even more interesting and appreciated. Both human and artificial intelligence chefs will have more ways to innovate and share their innovations, and a new class of food 'content creators' may emerge. The food industry may never look back.

Today, we may be stuck in a small 'corner' of food space, limited by the tools, techniques, ingredients and mindsets that our ancestors have held for thousands of years. Where could we go if we had access to new food preparation and cooking technologies, rapid innovation and dissemination cycles? What could we eat if we could remove the skill, cost and time barriers from preparing healthy food?

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Published online: 20 October 2023

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Competing interests

The authors declare no competing interests.

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