The future of vertical farming

the intelligent ecosystem

cambridgeconsultants
Part of Capgemini Invent

Introduction

Vertical farming offers an opportunity to increase crop production while reducing food miles and increasing product quality. Vertical farming can be the only way to grow crops close to urban centres where space is at a premium, and this has advantages in both reducing transport costs and increasing the quality of the delivered product.

However, the costs associated with vertical farming are higher than those of traditional farming methods – and are likely to remain so for some time. These costs can be split into the capital investment costs needed to build the farm itself, and the operating costs associated with running the farm. At a small scale, farm costs are dominated by capital investments, but larger farms quickly become dominated by operating costs, such as lighting, air and water management and labor. As the scale of the vertical farm installation increases, the operating costs dominate to such an extent that it becomes worthwhile to invest up front in making the environmental management equipment more efficient in the long run.

Although the efficiency of vertical farming can initially be improved through transferrable developments in lighting and automation from other market sectors, challenges unique to vertical farms will soon begin to become more relevant. The requirement for a Heating, Ventilation and Air Conditioning (HVAC) system for an office block are very different to those of a vertical farm, and so off-the-shelf lighting and HVAC systems will operate inefficiently when asked to meet the demands of a vertical farm. The future of vertical farming lies in system integration, thinking and addressing the unique challenges posed by a wider range of crops by addressing the environmental challenges up front.

Three areas will be discussed in detail in this paper:

- **Sensing** – how will existing technologies enable the closed -loop control of a vertical farming system to feed into both automation and environmental response?
- **Air management** – what are the challenges unique to vertical farming, relevant as a wider range of crops enter the market with different temperature and humidity needs?
- **Manipulation** – do the specific manipulations and environment of vertical farming automation need something new from robotics?

All examples of technology represented in this paper are projects undertaken by Cambridge Consultants.

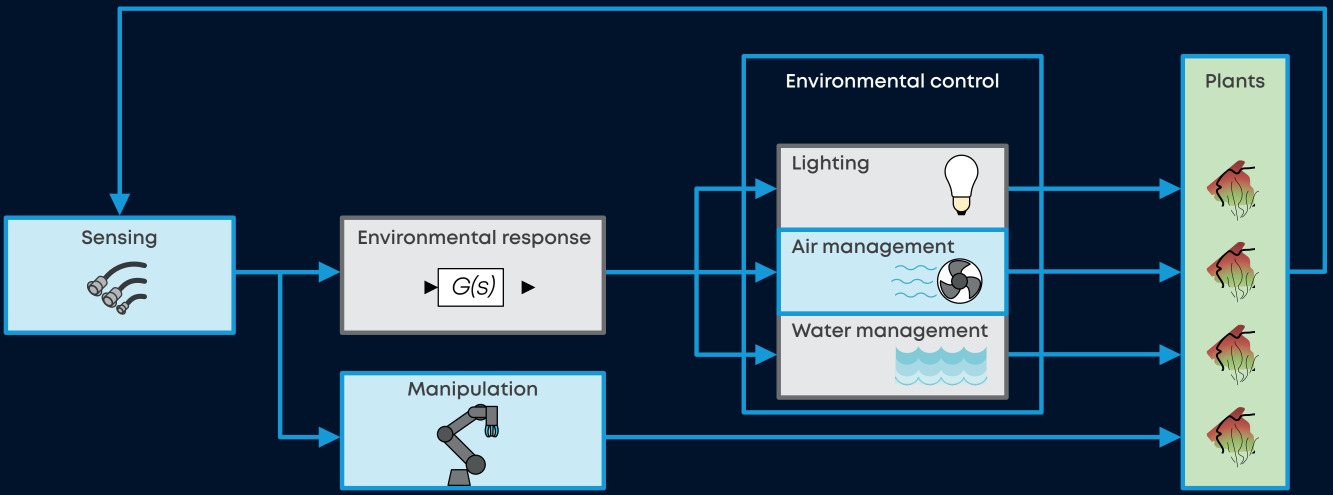

Figure 1: The ideal automated farm environment includes control of the complete environment, together with feedback from the plants on their requirements. We have just begun to realize the potential of this feedback and the limitations of the control systems.

Maturity of vertical farming technology

Sensing and automation have been making great strides in recent years. Vision systems and automated robotic pickers being two examples. However, the unique challenges associated with space constraints, physical sensitivity and environmental conditions leave opportunities to improve upon the current off-the-shelf technologies.

Described below are 'technology levels' associated with the three highest infrastructure operating costs of the vertical farm environment.

Lighting is the most significant, consuming ~70% of the energy of a typical vertical farm. While industrial standard LED or fluorescent lighting is sufficient for growth, it is inefficient. Increased Photosynthetically Active Radiation (PAR) light sources are becoming more readily available to reduce this energy cost.

Air management is the next most significant, consuming most of the remainder of the power budget, though it is greatly dependent on the crop type. The technology used here is a direct application of the same technology used for other facilities, such as office buildings, server farms, etc. The addition of CO_2 burners or decomposition has to date been a separate consideration.

Water management technologies are similar to those found in municipal water treatment facilities, with adaptation for the specific nutrient levels, pathogen detection and flow requirements.

All the areas of environmental control identified are currently commercialized at level 2. Due to the high energy cost of lighting, systems are under development to enable levels 3 and 4 in this area, though this will require an increase in low-cost sensing capabilities, such that information on the desired changes can be provided.

The drive for air management systems to reach level 3 and beyond comes from a desire to grow a wider variety of crops, some of which require conditions well outside those achievable by a typical off-the-shelf HVAC system.

Technology Level	Environmental Response	Automation
Level 1	Maintain fixed conditions	Manual labor
Level 2	Conditions manually selected	Assisted manual labor
Level 3	Respond to phase of life	Automation with manual intervention
Level 4	Control of crop quality though real-time response	Fully automated environment

Table 1: Environmental Response and Automation are currently at technology level 2/3. Reaching higher levels and higher potential for profitability in large-scale operations requires sensing beyond what is currently available.

Technology Level	Lighting	Air management	Water management
Level 1: Lifted directly from other applications	▪ Industrial lighting	▪ Use of standard HVAC system	▪ Automated irrigation system ▪ Nutrient dosing into the water
Level 2: Some adaptation of existing technology for application	▪ Efficient spectrum use, high PAR ▪ Focus only on the plant	▪ Higher power density ▪ Increased CO_2 levels	▪ Nutrient monitoring and control
Level 3: Specialized technology requiring custom development	▪ Adjustable spectrum, trigger growth phases when required	▪ Higher humidity ▪ Fully homogeneous conditions	
Level 4: Sub-system integrated with overall environment for an optimized system	▪ Closed-loop crop control through lighting	▪ Localized control of conditions	▪ Per plant nutrient dosing

Table 2: Environmental Control.

Sensing and environmental response

Plants have evolved a system of generating energy in a natural environment which varies depending on their latitude, overall climate and native ecosystem. The optimum conditions for a plant vary throughout its life cycle according to its origins, and yield can be improved by making sure these conditions are met. Humans have historically been the ideal means of inspection and assessment of crop conditions, and most vertical farms still rely on humans to inspect and manipulate the crops to maximize yield.

There are opportunities to further increase yield with the inclusion of automated feedback systems, enabled by intelligent sensing. Adjusting lighting, temperature and humidity, as well as monitoring plant health and directing automated pruning and collection systems, can further increase yield and overall efficiency.

Size and health

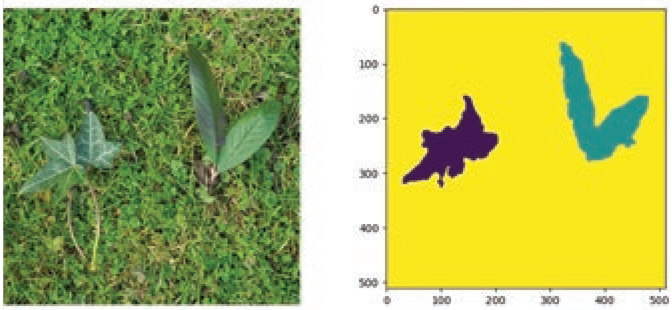

Figure 2: Cambridge Consultants weed detection vision system development, showing accuracy of a predictive algorithm on real-world data.

Identification of plants against a predictable background is relatively straightforward. Methods for assessing crop health have been utilized in various drone applications for field crops and are becoming more common indoors. Vertical farming is a much more tightly controlled environment and has much faster turnover and so nutrient deficiencies and diseases require a tailored approach. Deficiencies are less likely, but problems have a more immediate impact.

Detection of growth stage and flowering

To enable control of nutrients appropriate to growth stage and monitoring of appropriate interventions, such as triggering flowering or pollination, aspects of the plant need to be monitored which can go beyond the general shape.

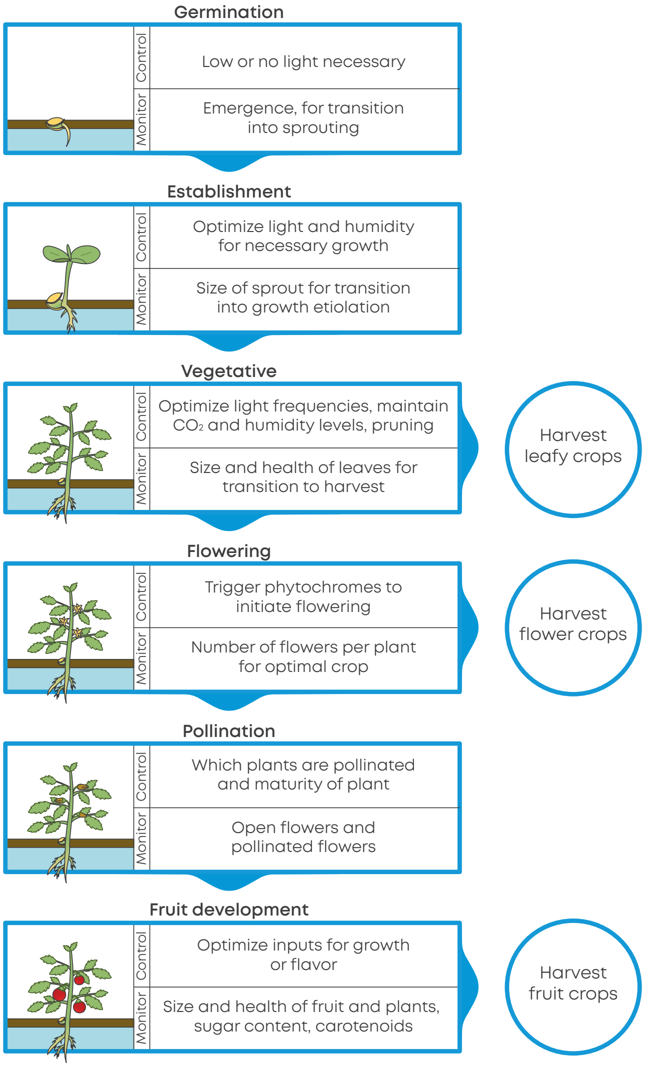

Figure 3: Growth cycle of a flowering crop and how monitoring and control can be used to optimise yield and profits.

Hyperspectral imaging is a method which has been demonstrated in many research programs, though due to its high cost it has seen limited adoption for in-farm assessment. Where current hyperspectral imaging focuses on gathering all of the information possible with broad band light sources and spectrometers, more targeted frequency detection for specific pigments will enable increases in processing efficiency, selection of lower capability components and an overall reduction in cost.

Typical technologies in use in this area include non-contact optical methods, though other opportunities for sensing exist. For instance, chemical release, nutrient uptake and plant stiffness are all indicators of behavioral changes in the plant.

Identification of individual structures (each leaf, each fruit, pests)

Figure 4: Low cost multispectral imaging developed by Cambridge Consultants makes detailed crop assessment accessible.

While general trends can be identified by looking at an overall plant, interventions can be made much more efficient through the identification of trouble areas. For instance, removing diseased leaves, targeted pest removal and yield estimation can be achieved if it is possible to distinguish individual structures within the plant. However, this requires higher resolution imaging and is more computationally intensive, changing the value proposition. Other methods of detection could also be used for detection of otherwise hidden structures, such as x-rays, sonic detection and laser interferometry, though these are all typically associated with much higher capital cost applications, such as automotive or production equipment.

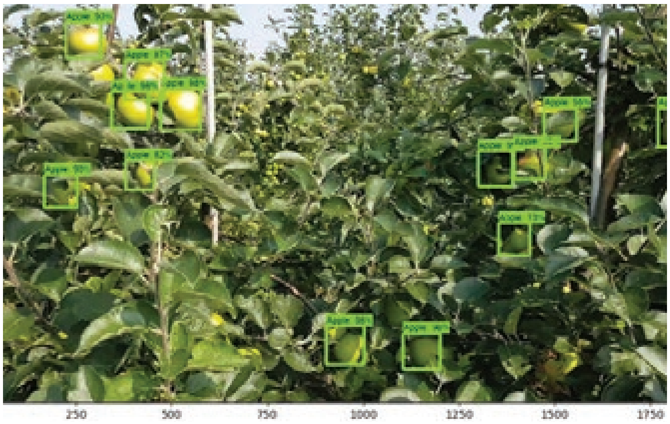

Figure 5: Fruit detection in a natural environment, utilizing footage from a cheap camera and machine learning.

The image shown in Figure 5 was taken from a moving, ground based autonomous platform in an orchard with natural lighting. This technology could be transferred to a system used to inspect multiple rows of plants in a more tightly controlled vertical farming environment.

Assessment of individual structure value (each leaf, each fruit)

Combining detection of individual structures, using optics and other sensors, enables those managing vertical farming to control the system in real time, responding to the health of the crop so that each fruit can be optimized. Within a single plant there might be some leaves or fruit in inferior condition, which would also compromise the quality of the rest of that plant. By isolating these plants, it is possible to ensure the maximum yield from every plant. Harvest can also be carried out at the optimum time per fruit or leaf, to maximize uniformity. Predictability of crop is one of the most valuable elements of vertical farming.

Detection methods are likely to include optical techniques, such as multispectral imaging and pattern detection through machine learning, but manipulation is also likely to provide some input. Human assessment of plants often includes touching and squeezing, a task that is extremely difficult for robots, that tend to have only a few tactile sensors, while humans have many thousands per finger. Context appropriate application of a small number of sensors, as well as the creation of new sensor types (see Figure 6), will bring robots closer to mimicking the abilities of a human.

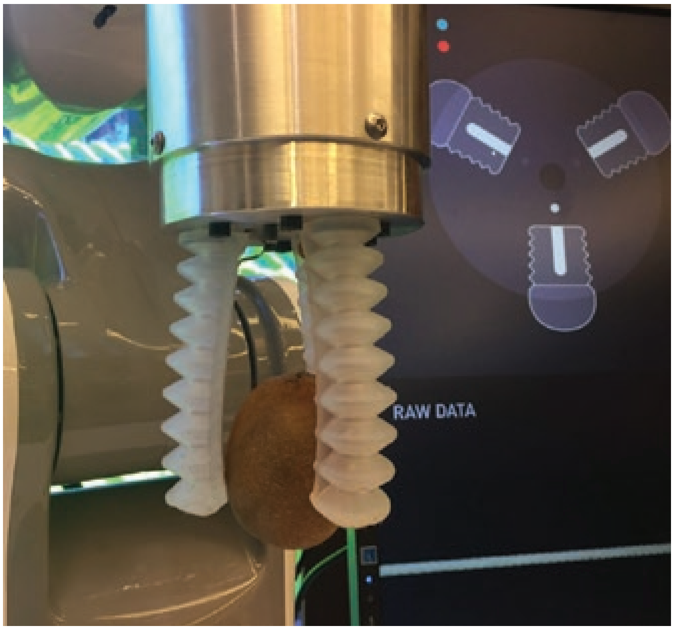

Figure 6: Slip sensors built into flexible end effectors enable minimum application of force for picking of fruit.

Air management

The controlled environments that humans are content to live in typically operate between 68 °F and 77 °F, with some form of white light and humidity between 20 and 40 %rh. Plants require much more varied conditions; temperatures between 59 °F and 83 °F, up to 100 %rh. This means that air conditioning and lighting systems originally designed for humans are either inefficient or incapable of delivering the optimum conditions for many plants.

Plants require anywhere from 200 to 400 W/m^2 (20 to 40 W/ft^2) of light. To maximize yield, this figure could be pushed as high as 700 W/m^2 for some crops. Assuming a favorable PAR, only 25 % of this power goes into the production of sugars. Combined with the energy efficiency of the electrical system, this results in a heat dissipation requirement of at least 170 W/m^2. If there are six layers of crop in a single farm, this gives > 1k W/m^2, even before the addition of any CO_2-producing burners. By comparison, a standard office air conditioning system assumes 100 to 150 W/m^2. The power requirements are much closer to a server farm, though the requirements become more demanding still (see Table 3).

Air temperature

Air temperatures outside of the optimum range can cause the plant to grow at a slower rate, reducing overall yield. In modern offices, cold air is released into the room at a far lower temperature than the eventual ambient desired. In a vertical farm this means the plants closest to the outlet would be too cold and those furthest away would be too warm. Additional ducting or alternative methods of distributing cold air throughout the space would increase yield, potentially eliminating the need for additional infrastructure.

Humidity and moisture

The moisture release rate of some crops are far higher than that which a typical HVAC system is designed for, and many environments require continuous operation at high humidities. Conventional cooling methods require cooled surfaces which reduce humidity, though at a rate which is closely tied to the amount of heat extraction capacity.

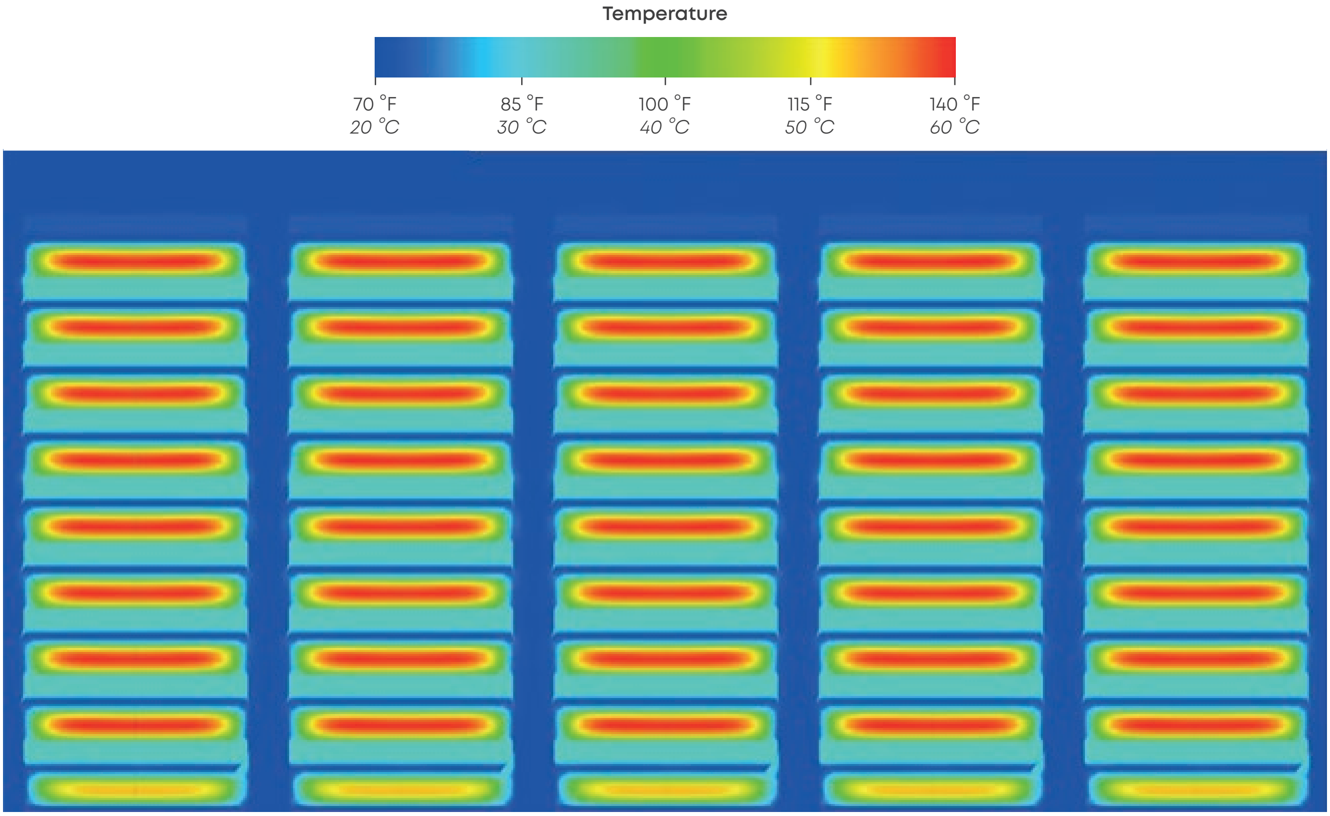

Figure 7: Modeling of distributed airflow inside a congested vertical farm demonstrates the challenge with maintaining consistent conditions throughout the plants.

Most of the crops that require high humidity also require high temperatures, but the large amount of heat within the system might still eventually result in a less than optimal humidity. The operating conditions for the HVAC system will also be well beyond the normal environmental requirements resulting in rapid performance degradation as components corrode or wear in high humidity.

Plant density and airflow

The environment within a vertical farm will become increasingly congested and the airflow highly restricted as highly dense crops vegetate. The volume of water in the farm creates a large heat sink, while the crops undergo cooling due to transpiration and absorb CO_2. Without applying gale-force winds, this will result in significant variability in environmental conditions between plants.

Summary

All these problems will be exacerbated as solutions are found for the automation challenges associated with vertical farming, reducing the need for human intervention. Denser plants mean more light, more heat, more moisture, less air circulation and more CO_2 production and usage. This will create a new set of challenges around the environmental controls.

A number of technologies have the potential to improve this situation. Distributed air management and cooling systems will allow for more uniform control of ambient conditions. Irrigation liquid could be used as a condenser for humidity reduction, or water vaporized over the plants for humidity increase. The immediate impact of these approaches on temperature, humidity and CO_2 can be modeled, such as in Figure 7. Given the unique challenges of the environmental conditions for a vertical farm and the very high power densities, a system level approach, considering the interactions between the plants, lighting systems, HVAC and any automation or human intervention has great potential to improve overall performance and yield.

	Conventional HVAC	Server farm	Vertical farming
Temperature range	68 – 77 °F *20 – 25 °C*	64.4 – 81 °F *18 – 27 °C*	59 – 83 °F *15 – 28 °C*
Humidity range	35 – 60 %rh	35 – 70 %rh	up to 100 %rh
Power density	10 – 15 W/ft^2 *100 – 150 W/m2*	200 – 300 W/ft^2 *2000 – 3000 W/m2*	20 – 70 W/ft^2 *200 – 700 W/m2*
Airflow requirements	comfortable	high	Low and uniform
Spacial requirements	control necessary close to ground	none	Control necessary throughout vertical height
Impact of small temperature oscillations	comfort changes	none	loss in yield

Table 3: Air management requirements for vertical farming vs conventional HVAC

Manipulation

There are some tasks which existing robots still find difficult relative to their human counterparts, such as identifying the correct level of ripeness, finding fruit buried in a canopy or harvesting only the best leaves from a plant. Increasing automation indicates a movement to a robotically manipulated farming system, with more automation of the stages in the plants' lives. This can reduce the need for access corridors for humans, increasing density, but the optimal solution with be neither a direct replacement for the human or a repurposed robot from another application.

Levels of automation

It is important to remember that both robots and plants can move. The different requirements of each crop will likely result in multiple solutions, some of which move the robot into the plants and some move the plants towards the robot.

Partially automated systems exist that allow human access to plants while increasing the packing density through movement of those plants. The need for access to the environmental infrastructure is still present and might introduce additional complexities through flexible pipework, distributed liquid beds or other dedicated hardware.

A robotic arm system which reaches into the plants with a manipulator offers a quick solution to the problem. However, robotic arms often have large inaccessible 'dead zones', usually related to their overall reach. The vertical height of the robot can introduce vertical clearance requirements, reducing density.

Moving the crop itself will typically work better for smaller crops, where the moving mass is minimized. This will require many more moving components, though typically of far lower complexity than the moving robot equivalent. Any moving system must also account for the infrastructure to maintain the correct lighting conditions, humidity, lighting and nutrients.

Sensing and dexterity

Humans have sensing and dexterity for fruit picking which extends beyond what is currently possible for robots. Visual inspection, texture and hardness detection and adaptive learning means a single human can pick a strawberry, gather marijuana leaves or collect lettuces without any hardware or software upgrades. There is a lot to learn from the way in which a human interacts in each of these situations. For a robotics system to replace the human, the distinct movements and feedback channels which will be most relevant must be identified for minimum complexity and maximum reliability. While moving plants is relatively straightforward, testing and picking fruit or pruning will be more difficult to mimic in a low cost way.

Summary

Robots for vertical farming have so far been largely based on repurposing of extremely complex arm systems, like those used in automotive production lines. There are great parallels to draw between the automation used in FMCG, where machinery custom to a specific product maximizes throughput with minimal human intervention, while performing complex, but repetitive movements. Vertical farming sits somewhere between the two, where the robot must exceed the performance of a human at tasks where a human is already capable.

	Industrial robotics	Vertical farming	FMCG Production line
Variation within a movement	None *pre-programmed*	Multiple *per plant, per growth stage*	None *predictable product*
Operation rate	1,000 – 20,000 per day	TBD	100,000+ per day
Capital cost per unit	$50,000 to $1,000,000s	< $100,000	$1,000,000s
Cost per operation (including amortisation)	$0.10 – $100	< $0.05	< $0.01
Movement variations	Infinite	< 10 for each family of crops	1
Safety considerations	Light barriers, no human access during operation	Food safety, microbial growth	Light barriers, no human access during operation
Environmental conditions	59 – 86 °F *15 – 30 °C* 35 – 70 %rh	59 – 82 °F *15 – 28 °C* 35 – 100 %rh	59 – 86 °F *15 – 30 °C* 35 – 70 %rh

Table 4: Requirements for robotics in vertical farms compared to other industries

Conclusion

Google's Director of Engineering Ray Kurzweil predicted a 'new vertical agriculture revolution' back in 2013, but it's clear that vertical farming is still a technology in its infancy. There is always a danger that emergent technologies never hit the 'critical mass' that means mass adoption forces the cost of the technology down, leading to greater adoption and then even more economies of scale. However, the economic and social drivers for vertical farming are clear, and technology exists that can be applied to make a real difference to the operating costs of vertical farming at scale.

There is a crossover from other industries too. There is a drive to increase the use of monitoring and sensing across many different industrial processes, with the goal of driving down energy usage, reducing downtime and having less chemical wastage. The technologies used to achieve these goals, such as low cost, low power IoT devices, AI and other machine learning techniques to help turn big data into insights, and increased autonomy of robotic systems, are all relevant for vertical farming.

The key point is that this technology does not yet exist in off-the-shelf form. An investment is needed to design a more efficient, targeted system that reduces operating costs in the long term by creating an intelligent ecosystem. This will cost more in design work initially, but the potential benefits to the companies that are willing to make that jump, and make it first, are enormous.

About Cambridge Consultants

Cambridge Consultants is a world-class supplier of innovative product development engineering and technology consulting. We work with companies globally to help them manage the business impact of the changing technology landscape.

With a team of around 800 staff in Cambridge (UK), Boston, San Francisco and Seattle (USA), Singapore and Tokyo, we have all the in-house skills needed to help you – from creating innovative concepts right the way through to taking your product into manufacturing. Most of our projects deliver prototype hardware or software and trials production batches. Equally, our technology consultants can help you to maximise your product portfolio and technology roadmap.

We're not content just to create 'me-too' products that make incremental change; we specialise in helping companies achieve the seemingly impossible. We work with some of the world's largest blue-chip companies as well as with some of the smallest, innovative start-ups that want to change the status quo fast.

For more information, please contact:

Niall Mottram, Head of Agritech
(Cambridge, UK)
Niall.Mottram@CambridgeConsultants.com

Roger Mainwaring-Burton, Agritech Innovation Lead
(Boston, MA)
Roger.Mainwaring-Burton@CambridgeConsultants.com

Andy Anderson, Director, Industry and Agriculture
(Seattle, WA)
Andy.Anderson@CambridgeConsultants.com

cambridge
consultants
Part of **Capgemini Invent**

UK — USA — SINGAPORE — JAPAN

www.cambridgeconsultants.com

Cambridge Consultants is part of Capgemini Invent,
the innovation, consulting and transformation brand
of the Capgemini Group. www.capgemini.com

Lit-WHI-039 v1.6 '2022_The future of vertical farming_Whitepaper'