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Remote Visual Monitoring System for Tunnel Grown Crops †

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Abstract: With soft fruit growers facing tighter margins due to changing economic circumstances and competition from low cost imports, it is imperative that growers can maximise their yield whilst maintaining a healthy crop. With longer growing seasons, disease can be a real problem affecting the health of the plant whilst also limiting the potential yield further impacting the grower. This project aims to provide a tool for the grower to remotely monitor a crop from anywhere with access to the internet. Using clusters of custom designed modules consisting of low-cost computing and imaging equipment, a system has been developed to monitor a crop throughout a growing season remotely. The system was able to power itself via renewable energy while capturing images of strawberry plants, inoculated with *Phytophthora cactorum*, via a fully customisable schedule for data collection, which reduced the risk of pathogen contamination of other crops by removing the requirement to physically visit the crop. The self-powered remote monitoring system is scalable by adding or removing clusters and lends itself to the collection of additional sensory data also.

Keywords: Digital Agriculture; Raspberry Pi; Data Collection; 3D Printing;

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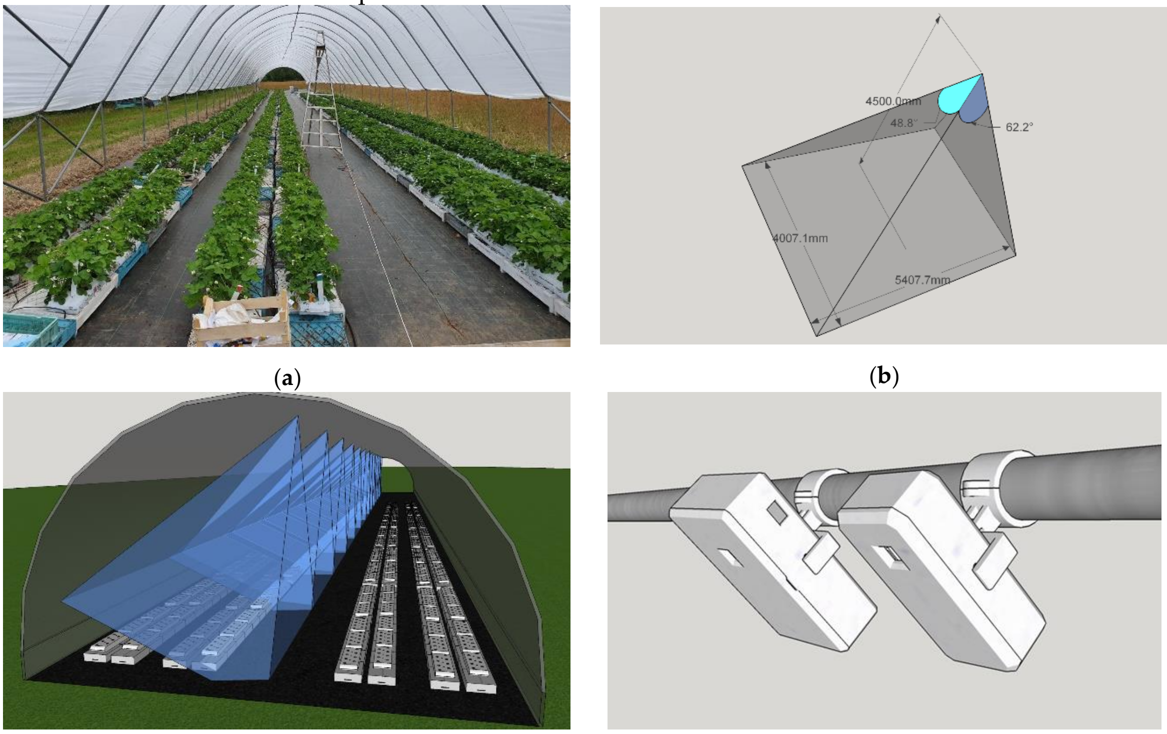
1. Introduction

The agricultural industry is facing a massive shortfall in labour, which in part is fuelling a drive towards automation of tasks within the Agri-Tech industry[1]. Using the soft-fruit industry an example, in the case of strawberries the UK is able to extend the growing season to more than ten months from March through to December, in part thanks to advances in crop management and the growing conditions for the crop, most notably table-top growing within an indoor polythene tunnel. This new growing season is very different from what it once was spanning from June-July[2].

With a longer growing season it is important to keep the crop healthy in order to maximise crop yield, many things can affect crop health including extremes of weather, pests and disease. Two most important diseases are powdery mildew and crown rot (caused by *Phytophthora cactorium*), which can result in yield losses from 20% to 70% in some cases [3]. Growers were once able to control diseases like powdery mildew in strawberry crop using various chemicals, however there are much tighter restrictions on what growers are able to use with many of the previous pesticides being completely phased out [4]. This leaves growers with twice the demand for soft fruit than what it was 20 years ago, but less options to achieve a profitable yield, also with the changing economic landscape due to the UK leaving the European Union. It is imperative that growers are able to meet the demand without relying on expensive imports and the negative impacts on the environment involved with the transportation of fruit from mainland Europe to the UK [5].

With automatic watering and dosing of nutrient systems adopted in most indoor growing environments (such as table-tap strawberry production), there is much scope for automation of the more tedious tasks, such as taking pH level and EC level readings of growing substrate that aid the adjustment of any nutrients to add to a watering schedule for instance. These tasks can be undertaken with the use of sensors placed within the growing medium at various locations throughout the crop, with data recorded and adjustments then made automatically based upon real-time available information. This does not, however, consider plant health. Does the plant "look" healthy? Is there any fruit on the plant? What colour are the leaves? Are the leaves misshapen? This paper proposes a system that will be able to help answer these questions, by introducing a monitoring system that can collect visual information about a crop grown within a semi-closed environment.

The proposed visual monitoring system was used to observe strawberry plants grown in coir bags within a remote poly tunnel at NIAB-EMR research farm in Kent in the UK (Figure 1(a)). Strawberry plants had been previously inoculated with *P. cactorum* in the late autumn 2019 before being cold stored over winter and then planted out late April 2020.



(**a**) (**b**)

(**c**) (**d**)

Figure 1. (**a**) The tunnel where the system was used is shown here, the crop used for the proposed system are the four rows on the left of the image; (**b**) The Pi Camera module coverage based from 4.5m height; (**c**) Using the stated horizontal and vertical field of view metrics of the camera modules aided in the planning of how to orient them within the tunnel; (**d**) Demonstration for Pi camera units mounted in-place along the top rail of the tunnel.

While initially as a part of ongoing research into strawberry crop disease to aid the development of a system that can recognise the presence of strawberry crop disease using AI, the implemented system is novel in its method of using low-cost equipment that is scalable to capture images of strawberry plants that could be used to assist in making crop management decisions, not just limited to disease recognition. Due to the devastating nature of crown rot to a strawberry crop and the lasting effects it has on a grower's site it was imperative to reduce the risk of contamination to other sites while collecting the ground truth dataset for developing AI engine. By installing the proposed system, we should be able to reduce this risk as the installation can take place before the plants are in place and, if necessary, be removed after the plants have been removed.

The tunnel in which the dataset was to be collected from, was in a remote area located within the research farm; there was no electricity or internet present. The only utilities available was water and the water pressure was used to power dosing system for the plants. The lack of power or internet connectivity were initial complications that eventually led to the low powered nature of the overall system and the increased versatility of the system, allowing it to be used in any location that has access to wind or sun and mobile data coverage.

2. Materials and Methods

2.1. Power requirements

Addressing the power requirements for a data collection system first, the overall daily power usage estimate was required in order to determine how much power was needed, the power considerations were as follows:

The system was comprised of several low-cost single-board computers (SBC's), in this case the Raspberry Pi Zero and Raspberry Pi 3B were used. These units were selected due to the low price, the computing power and wide range of compatible sensors. The system was set up to have clusters that were made up of a single Pi model 3B with two Pi zeros connected via USB with a coverage of 21.6 m^2 for each module and 51.8 m^2 per cluster, assuming a 20% overlap. These clusters were intended to simplify the wiring with only the main Pi 3B units requiring DC-DC step down conversion as the RPI Zeros would receive power via the Pi 3B. In 2016 Cloutier et al. [6] found the Raspberry Pi Zero draws 0.8w idle and 1.3w under an average load whereas the Raspberry Pi 3B draws 1.8w idle and 4.4w under an average load see table 1. That gives 160mA idle and 260mA under load for the Zero and 360mA idle and 880mA for the Pi model 3B.

The plants to be used for data collection occupied one half of a polythene tunnel of the size 8 m (width) x 70 m (length) x 4.5 m (maximum height). The total area of coverage required was 240 m^2, each of the modules would cover an area of 21.6 m^2 which would require 13 units without an overlap. However, to ensure good coverage and to aid any future image processing an overlap of 20% was introduced which brought the total required to 14.

Table 1. Power consumption of the modules used while idle and under a moderate load.

Module	Qty	Idle load watts	Avg load watts	Idle load mA[1]	Avg load mA[1]	Total idle watts	Total load watts	Total idle mA[1]	Total load mA[1]
RPI Zero	9	0.8	1.3	160	260	7.2	11.7	1440	2340
RPI 3B	5	1.8	4.4	360	880	9	22	1800	4400
					Total	16.2	33.7	3240	6740

[1] mA = 1000 × W / V, (V = 5v) [7].

With each image capture on each module and subsequent save to the networked drive taking no more than 15 seconds, giving this process more than enough headroom in terms of power by allowing 60 seconds for it to complete the expected power and current draw was then calculated (Table 1).

2.2. Energy Storage

The battery capacity for the units used in this project are 110 Ah, which would give an expected battery life of 33.3 hrs on a single charge for a single battery, requiring ~395 Wh of power (Table 2). To ensure there would be enough power for the system to function over the weekend period without draining completely and to provide a backup in case of failure of the battery, two batteries were used. In order to keep charging the batteries 150 w monocrystalline solar panels were used.

Table 2. Power requirements based upon expected use.

Module	**Qty**	**Idle time (mins)**	**Avg load (mins)**	**Idle (Wh)**	**Avg load (Wh)**	**Combined (Wh)[1]**
RPI Zero	9	59	1	7.08	0.2	7.28
RPI 3B	5	59	1	8.85	0.37	9.22
					Total (Wh)	16.48
					Daily (Wh)	395.8

[1] Idle Wh plus Average load Wh corrected for expected consumption for all modules.

Each of the 12 v 110 Ah batteries (Figure 2a) has ~1320 Wh. However, due to the battery chemistry being lead acid only ~50% of this is usable, as lead acid batteries do not tolerate discharging below this state of charge without reducing battery life and potentially causing permanent damage [8]. This leaves an estimate of 660 Wh of usable power in each battery.

(a) (b)

Figure 2. (**a**) Two 12V 110AH batteries used as the main power supply for the system; (**b**)Two 150W monocrystalline photovoltaic panels facing due south to maximize efficiency.

An average UK summer day can provide ~6 hrs of sunshine [9], with 6 x 150 = 900 w on average generated by each of the solar panels used (Figure 2b). Thus, two panels were ultimately used in conjunction with 2 x 110 Ah batteries to store the energy produced and reduce the risk of the system not being self-sufficient in terms of power.

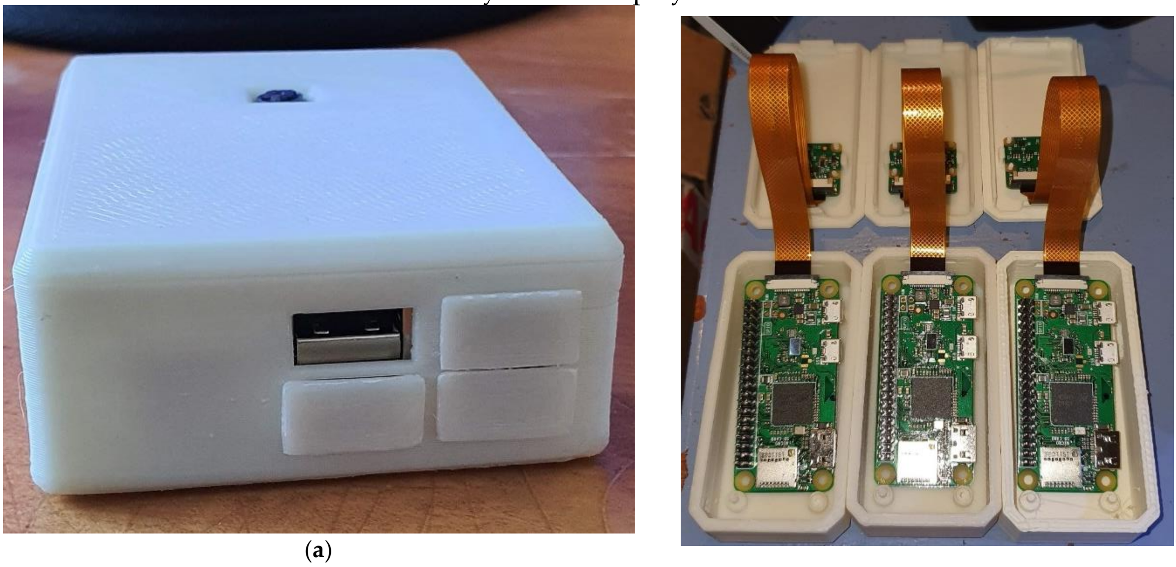
Solar panels can generate power without direct sunlight, meaning they still produce usable power on an overcast day; however according to work conducted by Premalath et al. [10] “compared to sunny day weather conditions, the energy yield during cloudy weather conditions is less”.

The system wiring consisted of 1.5 mm twin core cable which has a maximum rated capacity of 15A, which is greater than the worst-case scenario of ~13A should each Pi Zero and model 3B be under load all at the same time, which would be highly unlikely given that each Pi would be under load at different times to capture an image hourly with a slightly different pseudo random delay introduced of between zero to fifteen seconds.

Raspberry Pi units are designed to function 5.1 v and able to function at voltages as low as 4.63 v but a warning is displayed and random crashes can occur including corruption of the SD card inserted into the unit, from which the operating system runs [11].

In order to reduce the 12 v supply from the batteries down to a level that would power the Raspberry Pi units, a low-cost DC-to-DC voltage converter was used inline at each Pi 3B to reduce the voltage from 12 v to ~5 v. This ensured that there were no issues with underpowering the units to reduce the risk of SD card corruption.

Each Raspberry Pi 3B had 2 Pi zeros connected to it via USB cable, both the Pi zero and the Pi 3B's had custom cases designed and 3d printed (Figure **1**d, Figure 3a and Figure 3b) to house the units while offering protection from the fluctuations in the temperature and humidity within the polytunnel.



(**a**) (**b**)

Figure 3. (**a**) One of the Raspberry Pi Model 3B camera units with the bespoke 3D printed case to shield the device; (**b**)Three of the Raspberry Pi Zero camera units prior to being installed.

2.3. *Camera and Data storage*

The imaging sensor used for this project was the Raspberry Pi camera module v2, which is a low cost 8-megapixel camera with a sensor resolution of 3280 x 2464 pixels with the respective horizontal and vertical view field of 62.2 and 48.8 degrees. Figure 1c illustrates the visible area of the camera modules.

Images were captured as a compressed JPEG image of an approximate size of 2.4 MB, which would yield 357 images per 1GB of storage. The capture period was anticipated to take place over a period of 8-12 weeks, with 14 cameras capturing an image hourly for 12 weeks. This would generate a total of 28224 images; thus a 500GB drive was used to ensure that there would be adequate space to store the images.

Table 3. Comparison of available camera modules for the Raspberry Pi.

Model	**Chipset**	**Mega-pixels**	**FOV (°)**
RPI Camera v1	OV5647	5	54 x 41
RPI Camera v2	IMX219	8	62.2 x 48.8
RPI HQ Camera	IMX477	12.3	Lens Dependent
Arducam RPI Camera	OV5647	5	54 x 41
Waveshare RPI Camera IR-CUT	OV5647	5	75.7

Table compiled using information available from [12], [13] .

There are other options available for the imaging sensor available for the Raspberry Pi boards (Table 3). Of the five compared, the one with the highest resolution is the RPI HQ camera. However, it is also the most expensive option, at roughly twice the price of the sensor chosen; in addition, it requires a lens which is to be purchased separately, adding further cost.

2.4. *Data Connectivity*

The system was served internet access via mobile 4g Wi-Fi hotspot. The mobile router also had a 6400 mAh battery bank, which allowed the unit to be charged from the solar system during the day, ensuring sufficient power to maintain a live connection to the Pi module that acted as a server for the system. The hotspot had support for up to 32 Wi-Fi devices, which was more than adequate for the system to cover the entire tunnel.

2.5. Remote Management and Controller Software

The system was maintained via VNC which is a desktop sharing software that allows a user to perform tasks on the host machine from a remote location [14]. The camera that is connected to each Pi module was controlled via python script which was triggered with a cron job [15]. Using VNC allowed changing specific settings related to the image capture, such as the image compression, white balance, and scheduling image capture. It was also possible to check that the images were being captured properly and allowed a user to view and download captured images from the onsite SSD.

The system would benefit from a user-friendly interface to log into to amend scheduling and an error reporting system to warn of possible problems including but not limited to, low battery power, imaging sensor occlusions or sensor failure.

2.6. System Capability

In addition to collecting images, using the current platform as a base, this system could include capturing additional non-visual sensory data alongside images, because of the versatility of the Raspberry Pi platform it is a trivial task to add things like temperature and humidity sensors, EC level sensors, pH level sensors, light sensors or additional cameras that could possibly use different wavelengths of light other than the standard RGB sensors currently used. Work will also be targeted towards making the system more user friendly in terms of installation and maintenance, for instances, with adjustable clamps and making components hot swappable.

With the 20% overlap of the images it could also be possible to reconstruct the images as a 3D environment using image based 3D reconstruction such as the methods reviewed by Han *et al.* [16]. These reconstructions in turn could allow a trained agronomist to virtually visit a site and assess whether there are any problems without the need to physically visit a site. This could be extremely useful with in situations such as the current COVID pandemic where travel is restricted [17].

3. Conclusion

The system was installed at the beginning of July 2020 as a solution to obtain ground truth data under the imposed travel restrictions due to the Covid-19 pandemic, and the system was still operational at the beginning of October 2020, a runtime of 13 weeks. During this period the system was affected early on when the mobile Wi-Fi hotspot was configured on its default settings that put the hotspot into sleep mode after a period of inactivity less than the interval of the data collection trigger. The system had no issues in terms of power loss. The batteries were tested for voltage throughout the run period and they were 14.6 v (+/- 0.4v), and the RPI units operated in a “set and forget” manner until the system was removed. The system would have benefitted from an online web portal to manage the system, which is an area that will be exploited for the next growing season.

The tunnel was approximately 70 m long and 8 m wide with the targeted data collection area occupying 60 m x 4 m, the system was designed as clusters of 3 modules consisting of a central PI3B and 2 PI Zero units that took power from the central PI3B. By designing the system in this way meant there is an option to scale up or down as required by simply adding or removing a cluster.

The modules themselves show no signs of any condensation inside the 3D printed cases. Although the plan was to use the brackets to fix them to the tunnels centre pole, the inner diameter of the mounting bracket was undersized so cable ties were a very useful substitute as there was no access to a 3D printer on site to make replacement brackets.

The image quality was not affected by the module from which it was captured, with both the PI3B and the PI Zero units image quality being indistinguishable from one another without the filename which holds information including module ID and timestamp.

It is entirely possible to reduce the power requirements and cost of the system slightly by changing the cluster configuration, by replacing the central PI3B from each cluster with the PI Zero. It is recommended to have at least one cluster with the central PI3B to act as the file server. The PI3B module has much more computing power than the PI Zero, thus enabling it to potentially perform some computer vision tasks such as augmentation whilst collecting images, so it really depends on the requirements of the installation as to how the clusters are constructed. Representative costs for the units can be found in table A1 in the appendix along with an example of the equipment cost for the whole system based on prices as of January 2021 found in appendix c.

The system succeeded in capturing a dataset from a crop that had been artificially inoculated with *P. Cactorum*, a highly damaging disease, with a restrict access to prevent from its spread to other areas. The system was able to capture data both day and night and also had functionality to amend settings remotely and view and download data. The system used low-cost equipment and renewable energy for power (cost for which can be found in table A3) and was installed within a single day with 2 people. This system would suit any grower or research that has a site in a remote location where the requirements could include collection of other sensory data as well as images.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1. Cost per module

Module	Case[1]	Mounting Bracket[1]	RPI	Camera Cable	Camera	Power Cable	TF Memory Card	Total Pric
RPI 3B Module	1.15	0.23	33.9	1.5	23.1	2.5	7	69.38
RPI Zero Module	0.74	0.22	13.5	4	23.1	2.5	7	51.06

[1] Cost of 3D printer filament used, all other prices taken from www.thepihut.com [18].

Table A2. Data Connectivity Cost

Module	Per Month Y/N	Price
Wi-Fi Hotspot	N	128.76
Unlimited Data Sim	Y	20

Appendix B

Table A3. Power Generation and storage cost per system (max 8 clusters or 24 modules)

Module	Price
Solar & Wind kit [19]	666.79
110AH Battery [20]	44.06
100m 16A Cable	60
DC-DC Buck Convertor (pk 6)	8.99

12v IP67 Connectors (pk 20)	10.99

Appendix C

The installed system only targeted one side of a 70 m x 8 m tunnel with a maximum height of 4.5 m. There were 5 x RPI 3B modules with a total cost of £346 and 9 x RPI Zero modules with a total cost of £459, with a combined cost of £806.44 the mobile internet cost for the 3 months total cost was £188. The cabling and voltage conversion cost ~£79 and the power storage and power generation total cost combined was £846.

Total equipment cost for the system for the 3 months for half a 70 m tunnel was £2101. To cover the entire tunnel would simply require an additional 5 clusters, with a single Wi-Fi hotspot allowing a maximum of 32 modules there is no need to add another hotspot. A full tunnel coverage would cost £2928, including the additional voltage convertors and connectors.

As mentioned previously, the clusters can be changed from the central PI 3B clusters to a PI Zero cluster, meaning that 9 of the 10 clusters would be the more cost-effective PI Zero clusters which would bring the total cost for a full 70 m tunnel to £2865 for the 3 months.

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