Feasibility of detecting apple scab infections using low-cost sensors and interpreting radiation interactions with scab lesions

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ABSTRACT

Apple scab is a disease caused by the fungus Venturia inaequalis (Cke.) Wint, which can spread rapidly throughout orchards diminishing tree productivity and causing huge losses in marketable fruit. Efficient orchard reconnaissance and early detection of infections can inform fungicide applications for effective disease control and a range of new low-cost sensors offer a means of imaging orchards as the basis of scab detection. This study evaluates the potential contribution of three imaging devices: a multispectral (VIS-NIR) camera, thermal camera and a 3D sensor, for the detection of scab on young apple plants. In a controlled experiment, apple seedings were infected with scab and disease progression was imaged daily under natural illumination conditions in a glasshouse with minimal image processing. Whilst the thermal and 3D sensors images were deemed unsuitable for scab detection, the high-resolution multispectral imagery was exceptionally effective, with the NIR band (800–1000 nm) permitting the earliest scab detection due to the substantially lower reflectance of the fungal structures of V. inaequalis relative to healthy leaf tissue. We offer a model of near-infrared radiation interactions with the fungus and leaf interactions to explain reflectance characteristics of scab-infected leaves throughout the growth cycle of the pathogen. The simple, low-cost remote-sensing approach developed here holds considerable promise for providing timely information on tree infection to improve the efficiency of apple scab disease management routines.

1. Introduction

Apple scab is considered the most important disease facing apple production due the high disease susceptibility of most popular cultivars, widespread presence and the economic cost of control (MacHardy, Gadoury and Gessler 2001). Epidemics of apple scab rapidly spread throughout orchards causing huge losses of marketable fruit and long-term reductions in tree productivity. The pathogen occurs in all commercial growing regions, with the most devastating effects occurring in countries with cool, moist springs and high summer rainfall (MacHardy 1996). Current disease-protection methods require
abundant preventative fungicide applications that have a significant effect on production costs and negative impacts to the ecology, environment and the human health surrounding orchards (Papp et al. 2020). Responsive infection control strategies, informed by early detection of the presence of pathogens, could potentially reduce fungicide use significantly as part of an integrated pest management strategy (MacHardy 2000). Detecting apple scab infection on leaves early, before the disease becomes infectious, could improve the efficiency of chemical treatment strategies through timely application of curative fungicides and reduce crop losses. This smart treatment strategy could lessen the economic and environmental impacts of scab treatment over current approaches.

The lifecycle and epidemiology of apple scab is well defined. Apple scab, caused the ascomycete fungus V. inaequalis, begins its lifecycle overwintering in leaf litter as pseudothecia that contain ascospores, which are responsible for the primary infection phase (Figure 1). Rainfall and the presence of sunlight promote the ejection of ascospores from the pseudothecia, which are spread by wind to trees up to 200 m away (Belete and Boyraz 2017). Germination occurs when ascospores land on young leaf tissue and penetrate through the cuticle via germ tubes, with high humidity and free water on the leaf surface required for germination (Bowen et al. 2011). Temperature determines the hours of continuous leaf wetness required before germination occurs, known as the Mill’s infection period (Mills 1944; Stensvand et al. 1997). In spring the lower surfaces of leaves are the first to become exposed and often the first symptoms begin here, but once leaves are fully unfurled symptoms appear on both sides. No penetration of the epidermal cell layer occurs, instead the pathogen develops subcuticular runner hyphae from the germ tubes and melanoproteins create a nutrient transport system that diverts solute flow towards

![Figure 1. The lifecycle of the hemibiotrophic fungus V. inaequalis on apple trees.](image-url)
the site of infection (Delalieux et al. 2007; Jha, Thakur and Thakur 2009). Sexual reproduction of scab occurs within this subcuticular space as the hyphae develop into stromata, producing dense accumulations of conidia. As the conidia mature, they rupture the cuticle and become exposed, to then be released by rain and splash-dispersed to surrounding leaves and fruits. Infection by splash-dispersal acts as a secondary infection cycle that repeats until the end of the growing season (Belete and Boyraz 2017). Young leaves are most susceptible to secondary infection, becoming more resistant as they mature until the cuticle cracks and the leaf is susceptible again. Once the fungus ruptures the cuticle, the disease symptoms become visible macroscopically. The thick mass of conidia gives lesions a velvety texture and the melanin pigments contained within cells produce the distinctive olive-brown colour (Oerke, Fröhling and Steiner 2011). The diffuse, circular lesions that develop on the upper surface increase in size, raise and darken as the infection matures, ultimately leading to leaf senescence. Fruits are extremely vulnerable to scab after petal fall, especially during long warm periods of high humidity. Symptomatic olive-brown lesions occur on the apple skin that grow, darken and coalesce, eventually developing a corky texture as both pathogen and apple flesh become necrotic. Symptoms occasionally occur on shoots as light-brown swellings or reddish-brown spots but are rarely scouted for in disease assessments (MacHardy 1996). These visible symptoms provide the basis for apple scab diagnosis by agronomists in orchards.

Several studies have utilized remote-sensing systems for the detection of apple scab on the leaves of young plants, based on not only the visible symptoms but also the effect on the plant’s spectral and thermal properties to diagnose early infection. Delalieux et al. (2007, 2009a) showed how spectroscopy could detect scab infection early before the onset of visible symptoms through variations in the reflectance characteristics of leaves and their impact on ratio indices. Shortwave infrared wavebands associated with water content between 1350–1750 nm and 2200–2500 nm could distinguish infected and non-infected leaves at early stage especially as a ratio index \( R_{1480}/R_{2135} \) (Delalieux et al. 2009b). The chlorophyll \( a \) related Pigment-Specific Simple Ratio (PSSR\( a = R_{800}/R_{680} \)) (Blackburn 1998) was also capable of detecting scab at a later stage of infection. Hyperspectral sensing can be effective at detecting apple scab disease early through the stress response of plants but their utility for orchard use is challenged by their high costs, complex acquisition requirements and large volumes of data produced. Thermographic imaging of leaves infected with \( V. \) inaequalis displayed concentric spots of lower leaf temperature 1 to 3 days before the appearance of visible scab symptoms due to increased rates of leaf transpiration (Oerke, Fröhling and Steiner 2011). Areas of decreased leaf temperature exceeded that of the scab lesions by up to 80% when the first symptoms became visible which indicated the extent of infection and scab colonization greatly exceeded the macroscopic lesion size. Another strong indication of stress from leaf infection was the maximum temperature difference across a single leaf, which would be expected to remain homogenous across healthy leaf tissue and with higher differences occurring where transpiration rate was affected due to lesions. Measurements of maximum temperature difference are a well-established method for determining leaf infections (Lindenthal et al. 2005; Oerke et al. 2006; Jafari, Minaei and Safaie 2017); however, a drawback of thermographic images is the lack of diagnostic potential, as many biotic and abiotic stress factors display similar effects on transpiration (Oerke, Fröhling and Steiner 2011). A further study of scab infection found thermal sensing to
be effective at displaying symptoms earlier than that of fluorescence imagery (Belin et al. 2013). Infected leaves showed a decrease in Photosystem II quantum efficiency, but this is similar to that of young leaves and the protocols required for fluorescence imaging have been found to be unsuitable for use on tree crops (Delalieux et al. 2009a). 3D sensing has been used in past research as a way of segmenting thermal images, which can be difficult to distinguish from backgrounds, to detect scab, as well as to determine leaf curvature, orientation and growth rate that are all affected by scab infection (Chéné et al. 2012). There has been no further research into the use of 3D sensors for apple scab detection in plants likely due to the limited structural influence of scab on young plants and the negligible height of lesions on leaves in the early stages of infection.

While the initial research demonstrated the potential for the early pre-visual detection of apple scab in controlled laboratory settings, further progress towards operational techniques has stalled, likely due to the requirements for specialist equipment. The previous examples of spectrometry, thermography and fluorescence imagery are unsuited for detecting disease on leaves in complex orchard settings because they require controlled illumination sources, complex optics and computational hardware that increase the bulk and power requirements of systems (Lopez-Ruiz et al. 2017). Such sensors are also expensive, delicate and require significant training to acquire and analyse data making them unlikely to achieve widespread adoption as a solution in real-world orchards. However, there have been numerous breakthroughs in low-cost sensors used for plant phenotyping over the past decade including thermal imaging (Acorsi, Gimenez and Martello 2020; Vagelas, Papadimos and Lykas 2021), 3D imaging (Vit and Shani 2018; Paulus et al. 2014) and multispectral sensing (Kitić et al. 2019). These low-cost sensors are lightweight and designed for ease-of-use that may lend itself to imaging in orchard environments. In this context, the simultaneous deployment of many low-cost sensors has enabled the scaling up of measurements to facilitate the rapid imaging of large numbers of plants. Off-the-shelf systems for low-cost thermal and 3D imaging are readily available from suppliers, whereas finding a low-cost spectral imager is more challenging. Hyperspectral cameras (Behmann et al. 2018) and multispectral cameras used in agriculture and research including Parrot Sequoia+ and MicaSense RedEdge (Assmann et al. 2018) exist, but these systems cost several thousand pounds and they are primarily designed only for use with UAV systems, which further increases costs. A well-established method in plant phenotyping is to convert digital cameras into visible and near-infrared sensitive (VIS-NIR) cameras, as their CCD and CMOS sensors can detect wavelengths between 400 and 1000 nm (Verhoeven 2008; Lebourgeois et al. 2008; Morales et al. 2020). Whilst these systems do not compute radiance data as digital numbers that are converted into calibrated reflectance values, they do provide high-resolution near-infrared imagery that can display features as brightness values in grey-scale. In general, commercially available digital RGB (red-green-blue) cameras are low-cost, lightweight, durable sensing systems designed for ease-of-use. These cheap high-resolution camera systems could provide greater benefits than current expensive, low-resolution off-the-shelf multispectral cameras for detecting apple scab.

The low-cost sensing approach holds promise for establishing a practical method for the widespread survey of orchard trees for scab infections. As the first stage in developing this method, this study evaluated a range of low-cost (below £1,000) sensors for the early detection of apple scab under natural illumination conditions. Apple seedlings were
artificially infected with apple scab and images were acquired daily using a novel, low-cost, high-resolution multispectral camera system (with RGB, red-edge and near-infrared wavebands), thermal camera and a 3D sensor. Images were visually interpreted for symptoms in order to track disease development throughout the experiment. The purpose of this paper is to provide descriptive evaluation on the suitability for each individual sensor to detect scab from early to late stages of infection. The use of the high-resolution multispectral camera is a novelty for the detection of scab infection, and so the physical processes underpinning the results will be discussed. The overall aim is to determine which low-cost sensors display the potential for the early scab detection in apple orchards.

2. Methods

2.1. Plant material and inoculation

Young apple plants were propagated from the seeds of the economically important and highly susceptible cultivars of Gala and Braeburn, in an uncontrolled glasshouse at Lancaster University (Lancaster, United Kingdom) that simulated the natural illumination environment of an orchard. A total of 25 seedlings were grown in individual, uniform pots 80 mm in diameter; filled with young plant compost containing slow-release fertilizer and irrigated when required. All plants had been actively growing for 6 weeks and contained at least four unfurled leaves. Seedlings were selected as test subjects due to the simplicity of their structures and their lack of exposure to other potential sources of stress and infection. The young plants were artificially inoculated with apple scab in order to image daily from the known point of infection. V. inaequalis is well-suited to artificial inoculation and standard practice is to use conidia as these spores are abundant, easy to harvest and prepare, and suspend well in water, unlike ascospores (Moore 1964). An amalgamation of techniques was used to develop a low-cost, lab-free inoculation method.

Inoculum was gathered from infected leaves in commercial orchards of Jazz and Jonagold varieties in Herefordshire (United Kingdom) during October 2020. Infected samples were identified by assessing leaves that contained freshly sporulating lesions which correlated with those in the literature and orchard production guides (MacHardy 1996). Harvested leaves were placed in a paper bag to minimize condensation and frozen at −20°C in a sealed container, a common method of storing scab conidia (Szkolnik 1978). The inoculum suspension was produced by shredding 20 infected leaves, mixing with 100 ml of distilled water and shaking vigorously, a method adapted from disc cutting methods by Barbara, Roberts and Xu (2008) and Xu et al. (2008). An application of 5 ml of vegetable juice was added to help stimulate the fungal growth (Szkolnik 1978). The suspension was then immediately applied to leaves, which avoided the need to germinate spores on agar plates. Two methods of inoculum application were trialled. The first round of experiments utilized a drip method with a pipette, as used in Oerke, Fröhling and Steiner (2011), with the intention to produce scab lesions in precise drip locations that could help indicate if infection spread to other leaves. However, this method caused excessive runoff down the midrib of leaves, displacing most of the inoculum applied and resulted in development on only 2 of the 25 plants with a bias towards development along the midrib. The second method applied inoculum via an atomizer, with inoculum evenly sprayed across all leaves.


until saturated (Delalieux et al. 2007). The spray method proved more successful with 17 of the 25 plants developing infections. Each pot was individually covered with a transparent polythene bag to maintain a high humidity that promoted germination (Xu et al. 2008). Each pot was then carefully transferred to a warm, dark room, avoiding displacement of the inoculum from the leaves, and incubated for 48 hours. After the incubation period, each pot was transferred to the glasshouse where illumination, temperature and relative humidity were left uncontrolled.

2.2. Low-cost camera setup

2.2.1. Multispectral camera setup
Multispectral imaging was achieved using two co-aligned Raspberry Pi-based CMOS sensors with the infrared-cut filter removed from one (Figure 2). Each sensor was fitted with a 16-mm telephoto lens and was capable of taking 12.3MP images. This setup provided high-resolution sensing with adjustable focus and aperture. External bandpass filters (Midwest Optical Systems, Palatine, United States) covering the red-edge band (680 nm to 720 nm) and NIR band (800 nm to 1000 nm) were fitted to the sensors, so that the multispectral camera system delivered RGB, red edge and NIR wavebands. Both sensors were operated through a Raspberry Pi Compute Module 4 and I/O Board (Raspberry Pi Foundation, Cambridge, United Kingdom) that enabled simultaneous dual-camera image acquisition. The approximate cost of the setup was £500.

2.2.2. Thermal camera setup
Thermal and 3D imagery was acquired using cheap, off-the-shelf options. Thermal images were acquired with a CAT S60 smartphone featuring a FLIR lepton sensor (FLIR Systems, Inc., Wilsonville, United States), with a spectral sensitivity of 8–14 µm and a thermal sensitivity of 50mK. The cost of the CAT S60 smartphone was approximately £299.

Figure 2. Low-Cost multispectral camera development.
2.2.3. 3D camera setup

3D data were acquired with an Intel Realsense d435i stereoscopic camera (Intel Corporation, Santa Clara, United States) which processed a 3D model from dual NIR imagery aided by structured NIR light at a cost of £299, although this does not include the computational hardware required to acquire imagery, which would increase the price-point. 3D point clouds had an RGB texture overlay generated by the onboard camera to provide a true colour model.

2.2.4. Acquisition procedure

All three imaging systems were fixed to a variable friction arm and clamped to a platform directly above the imaging surface (Figure 3). The multispectral camera and 3D sensors were positioned 750 mm above the imaging surface, and due to differences in field-of-view, resolution and focal length, the thermal camera was positioned 300 mm above the surface. While this arrangement of sensors led to different imaging geometries between sensors, this was acceptable for the purposes of this study, where precise image co-registration was not required as the images from different sensors were ultimately interpreted manually, rather than through a quantitative procedure. Moreover, this variability in geometry is similar to that anticipated when using an array of different sensors in the field setting for operational scab detection.

Images were taken between 11 am and 3 pm from 7 dpi to 35 dpi. After both sets of experiments over 9000 images in total were taken from multispectral, thermal and 3D cameras. Information of the camera specifications and acquisition methods of the imaging system are displayed in Table 1.

2.3. Disease assessment

Apple scab incidence and severity were assessed through visual interpretation of the seedling images by a single trained individual to maintain consistency. Diagnosis of apple scab was based on the symptoms listed in production guides by the UK Agriculture and Horticulture Development Board, Penn State Extension T and in the works of MacHardy (1996). This method of manual interpretation of symptoms is equivalent to scouting performed by agronomists as a groundtruth. Disease severity was graded on an ordinal scale, a widely used descriptive method of classifying disease based on intensity of symptoms present (Bock et al, 2010). The symptoms to be observed were derived from the production guides and previous literature that used sensors to detect apple scab. The multispectral images were checked for spatial variability in reflectance intensity in Adobe Photoshop Software (Adobe Inc., San Jose, United States). Thermal images were searched in FLIR Tools for regions of localized cooling. Models acquired through 3D imaging were assessed for signs of deformation and stunting of leaves as well as to determine the span of leaves and plants to the nearest 5 mm in the open-source software MeshLab.

Each image was examined alongside a corresponding RGB image where scab could be identified based on the colour, shape and texture of lesions. Disease progression was assessed retrospectively from the most recent to the oldest images which allowed scab infections to be traced back to the initial location with greater accuracy. Infection severity was assessed daily using an ordinal scale (Figure 4). Early detection of apple scab was taken
**Figure 3.** Low-Cost image acquisition setup consisting of a multispectral camera, thermal camera, and 3D imager on a variable friction arm.

**Table 1.** Low-cost camera specifications.

|                          | Imaging System | Spatial Resolution | Field of View | Approximate Cost | Image format | Acquisition Software |
|--------------------------|----------------|--------------------|---------------|------------------|--------------|----------------------|
| a                        | Raspberry Pi CM4 | 4056 × 3050 pixels | 45° × 34°     | £500             | JPEG         | Linux (Raspberry Pi OS) |
| b                        | RGB Camera      |                    |               |                  |              |                      |
| c                        | VIS-NIR Camera with External Bandpass filter | 80 × 60 pixels | 46° × 36°     | £300             | JPEG         | MyFLIR               |
| d                        | Intel RealSense D435i Stereoscopic 3D Camera | 848 × 480 pixels | 87° × 58°     | £299             | PLY          | Intel RealSense Viewer |
| e                        | CAT S80 with FLIR Lepton Thermal Camera |                    |               |                  |              |                      |
| f                        | Variable Friction Arm |                    |               |                  |              |                      |
to mean detection of lesions before they become sporulating, in terms of the ordinal scale provided, this is at stages of low severity and earlier.

3. Results

3.1. Multispectral imagery

Preliminary observations revealed that high-resolution multispectral images had by far the highest potential for detecting scab at any stage, particularly the near-infrared band which displayed symptoms of scab earlier, clearer and to a greater extent than any other image type. Symptoms in the NIR band were characterized by dark lesions contrasted against asymptomatic leaf tissue of high brightness. Although similar symptoms could be observed in red-edge images, they were much less pronounced likely due to the spectral bandwidth being narrower than the NIR, which allowed less light to enter the sensor (Figure 5). Reflectance in the red-edge was also influenced by pigment concentrations unrelated to scab. For the remainder of this section of the paper, to demonstrate the ability of low-cost multispectral imagery for providing information on scab infection, only multispectral NIR band images will be compared against RGB, which are representative of the view of a human observer.

The NIR imagery provided information based on pixel brightness that was highly sensitive to scab symptoms from initial symptoms through to high severity infections. Infected tissue had a much lower brightness than healthy tissue making it easy to locate scab infections and distinguish them from other leaf features. At the initial symptom stage, infection points were difficult to identify visually through RGB imagery appearing as
a small, dark-green points along leaf veins roughly two weeks after inoculation. Infection sites would have been indistinguishable if not for retrospective analysis of the time series that tracked lesion growth backwards for comparison with NIR imagery (Figure 6). Lesions would remain as small points for several days after first detection until rapid growth would begin to occur, indicating that they were becoming sporulating. It was at this stage of moderate severity that infection could be identified by the naked eye if closely inspected, but determination of size and location of lesions was still challenging with RGB imagery.

The high-resolution multispectral imagery provided great levels of detail on the colour, shape and texture features of scab lesions on leaves and their development throughout disease progression (Figure 7). Symptomatic lesions at low severity were small, light-brown, circular and with a fuzzy texture with clearly separate points of origin. When zooming in to full pixel resolution, the circular lesions appeared more diffuse, expanding
Figure 6. The progression of apple scab symptoms on a single leaf from initial symptoms at 12 dpi to moderate severity at 22 dpi. Arrows indicate initial infection locations identified through retrospective analysis.

out from a central point along a main vein in a web-like pattern, and growing along venules with green leaf tissue visible in-between. The lack of contrast between olive lesions and green tissue, and diffuse borders made it difficult to determine the extent of lesions without image enhancement. In mature infections the network of fungal structures broadened, leaving little-to-no green tissue visible within lesions. As the mass of mycelium increased in mature lesions, they developed dark-brown and grey colours (Figure 5). The symptoms discussed were clearly detectable in otherwise healthy leaves, but in leaves that had suffered damage, due to abnormally high glasshouse temperatures, that resulted in brown, necrotic tissue it was more difficult to determine scab lesion location and extent (Figure 7 and 8).

NIR imagery was highly sensitive to scab infection from pre-visual symptoms to late-stage infections. In the early stages of infection, scab can be observed as a dark point along the midrib or vein of a leaf, 3 to 6 days before it is detectable in RGB. The central point of infection had a significantly lower pixel brightness than at the diffuse edges, where fungal structures are at their least dense (Figure 7). Symptomatic fungal structures appeared similar to those in RGB imagery but were more defined and were observed to cover a greater extent. Throughout the visual assessment of disease severity, NIR imagery would consistently rank infections at a higher severity than that of RGB images on the same day. Within infected leaves, there remained large areas of asymptomatic tissue without subcuticular mycelium being detectable in both RGB and NIR imagery. As lesions grew and merged, over half of leaf tissue would display fungal symptoms and would eventually begin to senesce due to the stress caused by the disease.

The ambient light environment had a major impact on the visibility of scab lesions on leaves in NIR imagery, and to a lesser extent RGB (Figure 8). Infection was easiest to detect under shade or cloud cover on bright days as this gave the largest contrast between healthy and infected tissue and greatest amount of detail on leaf features as colour and
texture information. Overcast days were also useful as light was diffuse and healthy and infected tissue could be clearly determined. Under stormy conditions, less light reached the plants resulting in dimmer images, with lower levels of detail (Figure 8). Direct sunlight was a major challenge. Specular light reflected from the leaf surface reduced the detail of the leaf texture in both RGB and NIR imagery, making it difficult to detect lesions underneath. Shadows cast across leaves also increased the difficulty of identifying scab lesions due to the reduced contrast between dark lesions and dark leaf tissue. Disease severity assessments of leaves under direct sunlight may be incorrectly attributed as having a lower severity compared to the same leaves imaged under shade.

3.2. **Thermal imagery**

Results from thermal imaging were inconclusive as it was extremely difficult to distinguish temperature changes from the plants stress response against external environmental influences of sunlight. In optimal imaging conditions of diffuse light, thermal
infrared emission measured regions of cooling by 1°C to 2°C in regions where scab symptoms were developing, although this could only be readily identified by using multispectral images to locate infected regions beforehand (Figure 9). Temperature differences within infected leaves were often significantly lower than those across the entire plant image that were influenced by shading, direct sunlight and the background material (Figure 10). Furthermore, the thermograms were extremely low resolution and compressed into JPEG format further degrading image quality. Hence, image resolution of leaves was much coarser for thermal compared to multispectral, making it extremely difficult to detect symptoms, especially during the early stages of infection when spatial variations in temperature are small, for the specified price-point of less than £500 per camera set.

### 3.3. 3D imagery

The results of 3D modelling of young plants were mixed. During early infection, there where were no discernible changes to plant architecture or leaf structure that would indicate scab infection. In some cases of severe infection, leaf deformation occurred after 50% of the surface was covered with fungal symptoms. Symptomatic lesions could be observed in the RGB texture overlays of the point clouds, but as with thermal imaging, the resolution of these were coarser than multispectral imaging, providing little benefit (Figure 11). There were several artefacts commonly observed in the 3D models that
### Figure 9.
Progression of apple scab infection in Thermal, RGB and NIR imagery over a 28-day period from 7 dpi to 35 dpi. Length of leaf in pixels from base to tip of a 50 mm leaf, and diameter of a 4-mm scab lesion included to highlight difference in image resolution between thermal and multispectral systems.

| 7 dpi | 21 dpi | 35 dpi |
|-------|--------|--------|
| ![Thermal](image1) | ![RGB](image2) | ![NIR](image3) |
| ![Thermal](image4) | ![RGB](image5) | ![NIR](image6) |

### Figure 10.
Temperature variation across different features of a A) thermogram and corresponding B) RGB image.

| Label | Feature                  | Temperature °C |
|-------|--------------------------|----------------|
| 1     | Fungal structure on leaf | 29.5           |
| 2     | Infected green leaf tissue | 29.5          |
| 3     | Healthy leaf (in sun)    | 30.6           |
| 4     | Potting soil             | 28.0           |
| 5     | Imaging surface          | 33.7           |
affected the model quality that were attributed to the coarse depth resolution. An NIR texture overlay could be registered to the generated point cloud at finer depth measurements which helped improve model quality (Figure 11). The 3D imaging did not provide the ability to detect scab infections at the early stages but did provide a benefit as a supplementary sensor for measuring sizes of leaves and lesions during assessment.

The results are clear in showing that multispectral imaging is the superior method to thermal and 3D imaging for the detection of apple scab from early to late stages through subjective visual interpretation. From the tested sensors, only the high-resolution near-infrared imagery could detect lesions before they become sporulating on young plants and could be used to aid detection of symptoms in RGB imagery where lesions are less pronounced. Low-cost thermal imaging did not provide suitable data and is not recommended for further research at this stage. There may still be potential for 3D imaging to aid research in developing a scab-detection system, by acting as an ancillary technology supporting multispectral assessment through generating 3D models and spatial measurements of plants, leaves and lesions, but it cannot be used alone to detect early symptoms of scab, only at late stages of the disease through the onboard RGB and NIR cameras.

4. Discussion

4.1. Radiation interaction with scab lesions

Reflectance characteristics of leaves in the VIS-NIR range show the greatest potential for detecting scab infection on apple plants. The visible domain is where the light absorbing pigments, specifically chlorophyll in the palisade cells, have the greatest influence on healthy leaf tissue reflectance. The melanin pigments in conidia have low reflectance in blue wavelengths increasing exponentially towards red giving a brown-coloured reflection. This colour does not contrast against the chlorophyll in green leaf tissue making it
difficult to differentiate early symptoms from leaf tissue at early stages and to determine extent of scab lesions in later stages.

In healthy leaves, a small fraction NIR radiation is absorbed by cells with the majority being reflected back through the upper surface or transmitted down through the leaf (Woolley 1971). Multiple scattering of photons causes reflectance to be much greater than the reflectance of visible light where absorption of pigments results in single scattering processes (Ustin and Jacquemoud 2020). The reflectance of NIR light in leaves is determined by the internal cellular structure, especially in the spongy mesophyll layer at the cell membrane and air interfaces where light is reflected and refracted (Gausman and Allen 1973). NIR reflectance increases with an increase in number of intercellular air spaces because light is scattered in passing from hydrated cell walls with a higher refractive index than that of intercellular air and is much less likely to be absorbed (Allen et al. 1970). In scab lesions, the dense accumulation of subcuticular conidia has significantly lower volume of air cavities than the mesophyll layer that reduces the penetration into the spongy mesophyll of the leaf and instead interacts with the subcuticular matter. Lesions contain masses of individual cells where near-infrared light undergoes similar cell wall interactions and scattering. Unlike the spongy mesophyll layer, there is little intercellular air space, increasing the likelihood of scattered light being absorbed within the conidia.

Figure 12. Interaction of NIR light with infected and asymptomatic leaf cross-sections.
(Curran 1989). The scattering and absorption of NIR light results in little radiation being reflected up through the surface and appear as regions of low brightness in NIR imagery and reduced transmission through to the mesophyll layers (Figure 12). The symptoms visible in NIR imagery are a result of the fungal structures themselves reducing reflection, rather than the plant response to disease as *V. inaequalis* does not penetrate the epidermal layer or damage underlying cells in a way that would affect mesophyll layer structure (Bowen et al. 2011; MacHardy 1996). Due to the novelty of the method, and the limited research on the absorbance, reflectance and refractive characteristics of phytopathogenic fungi at near-infrared wavelengths it is difficult to determine the exact cause of this phenomena and further study into the interactions of *V. inaequalis* with electromagnetic radiation is recommended.

### 4.2. Apple foliar sensing requirements

Only high-resolution multispectral imagery from converted digital cameras was found to be effective at detecting scab on seedlings from initial symptoms to high-severity infections. Low-cost thermal imagery was less effective despite well-documented research into leaf temperature changes caused by scab (Oerke, Fröhling and Steiner 2011) and other fungal diseases (Lindenthal et al. 2005; Jafari, Minaei and Safaei 2017). Unlike the current study, previous experiments were undertaken in controlled conditions with expensive, high-end equipment that could accurately measure temperature changes at a higher spatial resolution than the FLIR lepton. Previous studies have controlled temperature and illumination conditions providing useful insights into the thermal properties of scab-infected plants and the disease influence on leaf transpiration, but this would not be feasible for field experiments. The low resolution and major influence of sunlight on the results meant that the challenge of imaging complex adult trees, from a greater distance with even less control over conditions restrict the potential of current low-cost thermography systems for scab detection. Proprietary software was required for advanced analysis of the FLIR thermal images, which restricted the ability to determine maximum temperature difference features in this study. If developments in thermography technologies further reduced the price of thermal imaging cameras with high resolutions, there may be scope to review the recommendation for use in certain circumstances. 3D imagery had not previously been utilized in the detection of scab based on deformation scab indices on leaves but had been used as an ancillary technology to aid segmentation of leaves (Chéné et al. 2012) and to provide point clouds for 3D spectral modelling. There may still be potential for 3D sensors as an ancillary technology in tree-level scales, where models can be acquired from a greater distance. There are several low-cost 3D sensors that use different techniques to determine 3D information of plants, although the Intel RealSense was selected based on the recommendations of outdoor use by Vit and Shani (2018), other methods may be found to be more suitable, and as with thermal imaging further developments in the near future may improve the feasibility of use. Although thermal and 3D technologies should not be ruled out in future, they are not recommended for low-cost detection of scab as the results achieved by the multispectral camera are far superior. One benefit using a single multispectral camera is the lack of requirement to build a system based on sensor fusion of multiple image types which could drastically increase the cost and complexity of a device.
4.3. Directions for future research

Modifying digital cameras can open disease detection up to growers of small and large orchards in both developed and developing nations. They are cheap, rugged and are based on technology that most people can use. The concept of converting RGB cameras into multispectral imaging systems would work for most commercial digital cameras but not all have the adaptability of the Raspberry Pi based system. The most important factor to consider is the image resolution, as scab symptoms are several millimetres in diameter which can be challenging when using imagery acquired from a platform at a distance from trees. The second important factor is adequate control over the acquisition settings that affect brightness, focus and clarity. The influence of specular reflectance of solar radiation has been significant detriment to thermal and 3D and has been shown to degrade clarity in multispectral images, this problem can be mitigated by reducing the light reaching the sensor through shorter shutter speeds and smaller apertures. Similarly control of focus is important and maintaining an appropriate shutter speed to achieve maximum detail in an image. In this experiment no post-processing took place as images were saved as JPEGs, post-processing of RAW imagery could also help mitigate the effects of sunlight and shade in detecting scab symptoms on leaves. Automating the image acquisition process is necessary in order to rapidly capture data across orchards for disease detection and having a multispectral camera operating remotely and automatically adjust settings based on environmental conditions would achieve this.

A limitation of this study is the labour-intensive and subjective nature of severity ranking. Whilst appropriate at the current stage of comparing different sensing technologies, for larger trials on mature trees, a more objective approach of ranking disease severity, based on percentage tissue infected would be preferable. Using machine learning, rather than manual estimations can improve the objectivity of results. Several studies have devoted research in using RGB images from consumer cameras to identify apple scab and other diseases accurately in complex environments using machine learning (Chandel, Khot and C. 2021; Jarolmasjed et al. 2019) and by extension deep learning methods (Chao et al. 2020; Jiang et al. 2019; Liu et al. 2018; Zhong and Zhao 2020). Using machine learning to automate identification, classification and quantification of scab could improve labour costs in data analysis to compliment the low-cost sensors for a comprehensive economical solution to apple scab detection. To reliably detect scab early would require accurate labelling as a groundtruth. This study demonstrates the ability for a rater to determine scab infection even at early stages of infection. One major challenge of remote sensing for disease detection in crops is the potential for multiple biotic and abiotic stresses to act concurrently upon plants that can lead to large variation of symptoms displaying on leaves. Further study into the effect of other biotic and abiotic stresses on leaves and scab lesions would be required to improve classification confidence in real-world detection of apple scab.

5. Conclusion

The aim of this research was to find a suitable low-cost sensing system for detecting apple scab disease on young apple plants. A sensing system consisting of a multispectral, thermal and 3D camera was constructed to observe scab progression of artificially
infected plants in a glasshouse. It was demonstrable that low-cost sensing of apple scab through multispectral imaging is not only feasible, but ideally suited due to the unique epidemiology of *V. inaequalis*. NIR band images clearly displayed the extent of fungal structures against the high brightness of asymptomatic leaf tissue, and the high-resolution provided insight on the growth of scab and diagnosis based on shape features. Low-cost thermal images were unsuitable for diagnosing scab at any stage due to the poor resolution, and 3D sensing did not provide significant benefit when used alongside multispectral imaging.

This study displays the feasibility for low-cost detection of apple scab through the novel use of VIS-NIR-based multispectral imagery. There is a great scope for this technology to be utilized to improve the efficiency and economics of scab management strategies. This research has built upon the knowledge from previous work and taken it further by imaging in uncontrolled lighting conditions, which are to be expected in the field. To achieve its potential, multispectral imagery must be scaled up for image acquisition and classification of apple scab on mature apple trees by developing methods of automating image acquisition and analysis.

**Key Highlights**

1. A low-cost high-resolution multispectral camera was developed on a Raspberry Pi system.
2. High-resolution near-infrared imagery could detect apple scab earlier than RGB imagery.
3. Near-infrared reflectivity of scab lesions was much lower than asymptomatic tissue.
4. The high density of scab conidia increases scattering and absorption of near-infrared light.
5. Multispectral imagery and automated classification may enable early detection of scab in orchards.

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**Data Access Statement**

All research data supporting this publication are directly available within the publication.

**Disclosure statement**

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