Project title	Combined thermal and visual image analysis for crop scanning and crop disease monitoring
Project number:	CP 60
Project leader:	Rodney Edmondson WHRI
Report:	Final
Previous report	None
Key staff:	Student NGUYEN PHUONG NGOC Rodney N Edmondson Supervisor Dr Nasir Rajpoot Supervisor
Location of project:	WHRI and Computer Dept, University of Warwick
Project coordinator:	Alan Davis
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Date project completed (or expected completion date):	01 Feb 2010
Key words:	Thermal imaging, image processing, pests and diseases

Signed on behalf of: Warwick HRI

Brian Thomas 28 April 2010

Signature:…………………………………… ***Date***: ……………………………

Name: Professor Brian Thomas

Acting Director and Head of Department

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

CONTENTS

Grower Summary

Headline

Thermal imaging can be used to detect small differences in plant temperature and the first year of this project has demonstrated the feasibility of developing custom software for routine thermal scanning of crops.

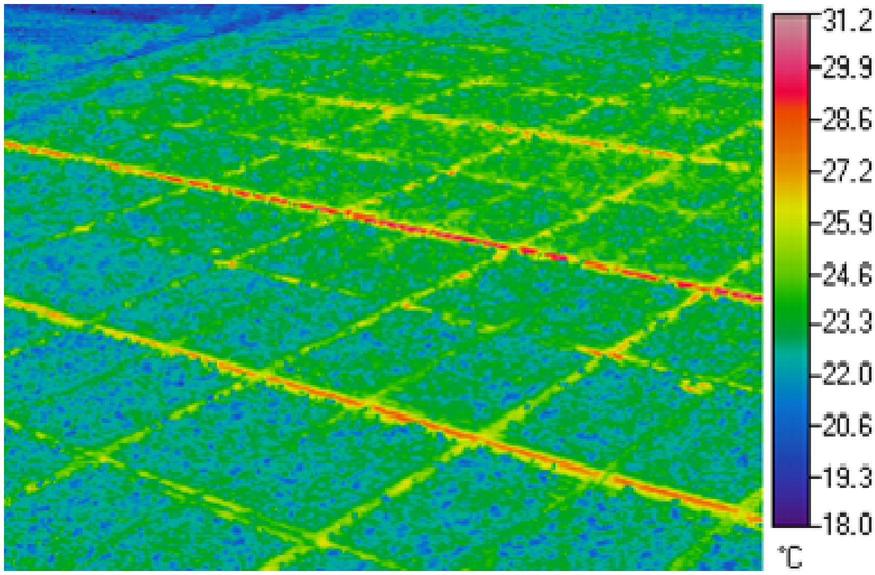
Background and expected deliverables

Thermal imaging can be used to detect very small differences in plant temperature caused by, for example, reduced transpiration due to disease or stress symptoms and there is ample evidence in the scientific literature that thermal imaging has the potential for early detection of plant disease and stress before other visual symptoms become evident. However, the temperature of an area of crop is highly dependent on position and aspect and may be affected by factors such as shade, position and tissue type and the early appearance of anomalously high temperature effects in individual plants can be difficult to detect against the variable background temperature of a crop. The project will develop new techniques for crop scanning and monitoring using a combination of visual and thermal image analysis techniques with the aim of building a 3-dimensional thermal profile of a crop using overhead crop imaging and scanning. The observed temperature at any point in a crop can then be compared with the expected temperature at that point and the difference used to test for temperature anomalies at that point in the crop. Plants or tissues with relatively high temperatures can be flagged as problematic and the grower can then carry out immediate checks on those plants.

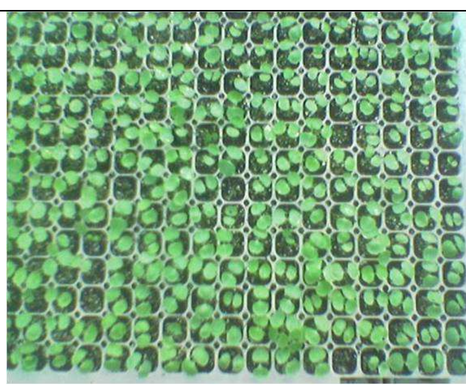
The project will aim to deliver custom software for improved detection of individual thermal crop anomalies relative to the normal background temperature of the healthy crop. The software will be potentially valuable for routine monitoring of the health of a crop during normal crop production.

Summary of the project and main conclusions

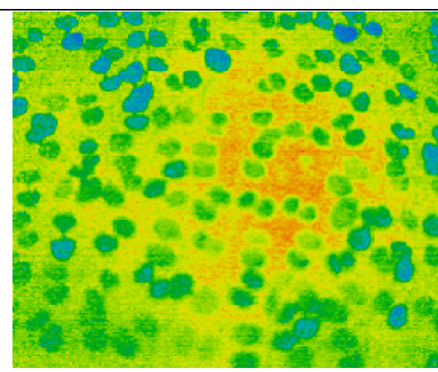
The project has shown that it is feasible to use thermal cameras to measure plant temperature in a commercial environment. The image below distinguishes macro-features such as tray boundaries and whole trays but it is unlikely that anomalies at the individual plant level would be detected at this scale of observation.



However, the following images show a visual image of a tray of seedlings and a thermal image of part of the same tray (the images do not fully match). The thermal image shows evidence of a warm spot (red) which demonstrates the potential of the thermal camera for detecting thermal anomalies. The warm spot appears to be associated with the soil surface itself which may suggest an irrigation effect. Thermal plant images in the area of the warm spot are yellower than in the rest of the image which indicates that these plants had a higher temperature than the rest of the crop. This example shows the potential of a thermal camera for detecting temperature anomalies in a crop but also illustrates some of the difficulties of using automated crop scanning for anomalies.



Visual image



Thermal image

The thermal camera imaging system used in experimental trials is shown below.

The emphasis of the first year of the project was to develop a protocol for collecting and processing thermal images for thermal image analysis. Results so far have shown that detection of even very small temperature differences in plants is practicable and feasible. However, it is also important to understand that all the images shown in this report were collected under bright sunshine. Our experience is that it is much more difficult to obtain good thermal images on dull overcast days or under conditions of low light and this may prove a major challenge for early detection of thermal anomalies.

We have shown that water stress effects can be routinely observed under suitable conditions but we have not yet been able to demonstrate thermal effects due to pests and diseases. However, it should prove feasible to detect disease effects where these effects involve significantly reduced plant transpiration rates and this will be addressed in the next phase of the project.

We have shown that the thermal images contain useful plant temperature information that can be associated with applied stress treatments. However, as anticipated, the images also contain substantial thermal noise due to positional and trend effects and discriminating useful thermal information from noise effects is challenging. The development of custom software capable of automatically distinguishing thermal effects indicative of plant disease from background noise effects will be essential for successful application of thermal imaging for routine plant screening.

Finally, the thermal camera used for this project was adequate for single stationary images but is not suitable for automated crop scanning. Recently available modern thermal cameras at realistic prices have composite video outputs and USB interfaces and can be programmed and controlled from a PC interface. Provided suitable software can be developed for routine automated analysis of thermal video images, these cameras could be used for continuous automated crop scanning using a moving boom located close to the crop surface for high resolution close-up crop images.

Financial benefits

Routine thermal crop scanning during production can potentially provide substantial financial benefits to growers from early detection of crop health problems. Suitable cameras and computer systems are available off-the-shelf and overhead camera mountings can be attached to existing overhead glasshouse structures. However, substantial further research will be needed to produce a practical crop scanning system and the main cost of the system is likely to be the software needed to control the cameras and to analyse the images.

The cost of installing a crop scanning system in a glasshouse would be a major capital investment but the benefits would be long-term and cumulative. Modern glasshouses have very large beds and crops are often inaccessible for direct human visual inspection. Under these circumstances, the use of automated imaging systems providing close-up visual and thermal images of growing crops could provide substantial financial benefits including early detection of pests and diseases.

Action points for growers

None at present.

Science Section

Introduction

The project was an HDC Studentship and a student was appointed in mid-February 2009. Unfortunately, he did not return from the Christmas break in 2009 and it has been necessary to terminate the studentship. The student did not provide a summary of his progress before departing therefore this report is based on partial information only and the report cannot provide a proper scientific summary of the work done by the student during his 10 month period at WHRI. The report is as complete as possible and gives an overview of the work done in collecting thermal images at WHRI during the period February-December 2009. A successful application has been made to HDC to continue the work and a student will be appointed to carry on the project in October 2010.

Materials and methods

The image analysis work was planned to have two components, the first was to develop super-resolution to improve thermal image quality and the second was to develop image registration to superimpose thermal and visual images on a single model. All image analysis processing work was done using the image analysis toolbox of Matlab. Progress on the two components is summarized below.

Image super-resolution

Commercial thermal cameras are commonly available in three pixel number counts:

- Low Resolution - 160x120 (19,600 pixels)
- Medium Resolution - 320x240 (76,800 pixels)
- High Resolution - 640x480 (307,200 pixels)

The 'high resolution' array is very expensive and is still quite low resolution compared with digital visual cameras. Hence any method that can enhance thermal resolution is potentially valuable for improving the sensitivity of thermal crop imaging.

Resolution can be improved by locating a camera near to the surface of a crop to obtain high resolution images of a very small area of crop. The camera can then be scanned over the entire crop area to give a high-resolution mosaic of the entire crop surface. However, there can be practical and theoretical limitations that prevent the location of a camera very close to a crop surface and super-resolution techniques must then be used if enhanced resolution is required.

Super-resolution (1) enhances the resolution of an image by merging information from a number of overlapping images. In effect, the resolution of a target image is improved by using pixels from overlapping adjacent images to increase the pixel count in the target image. Super-resolution is particularly suitable for video images from a scanned glasshouse crop where it can be assumed that crop images on successive video frames are identical apart from a horizontal shift.

Fig 1 shows four images of the same tray of plants each with resolution 320 x 240 pixels where each image has been shifted by approximately 1cm left or right or up or down.

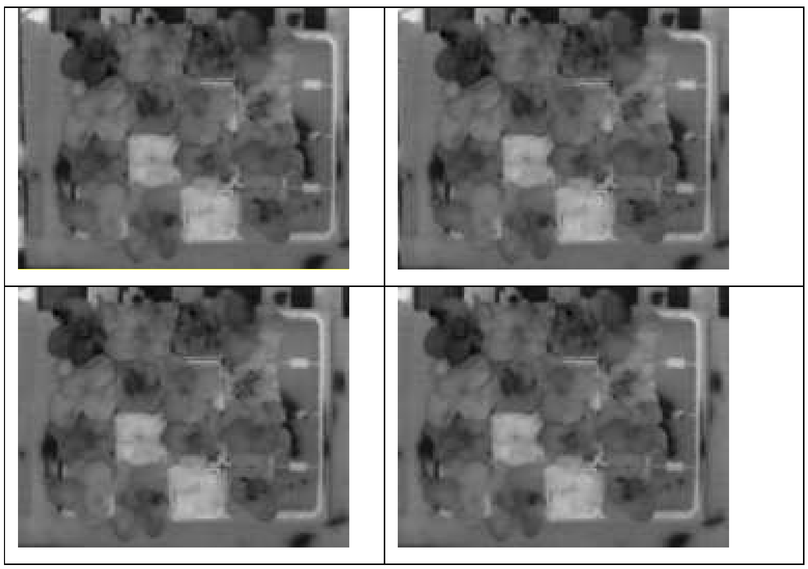


Figure 1: Four low-resolution (320 x 240) shifted images of the same tray of plants

Fig 2 shows a low resolution image (left) and a higher resolution image (right) obtained by super-resolution of the four images shown in Fig 1.

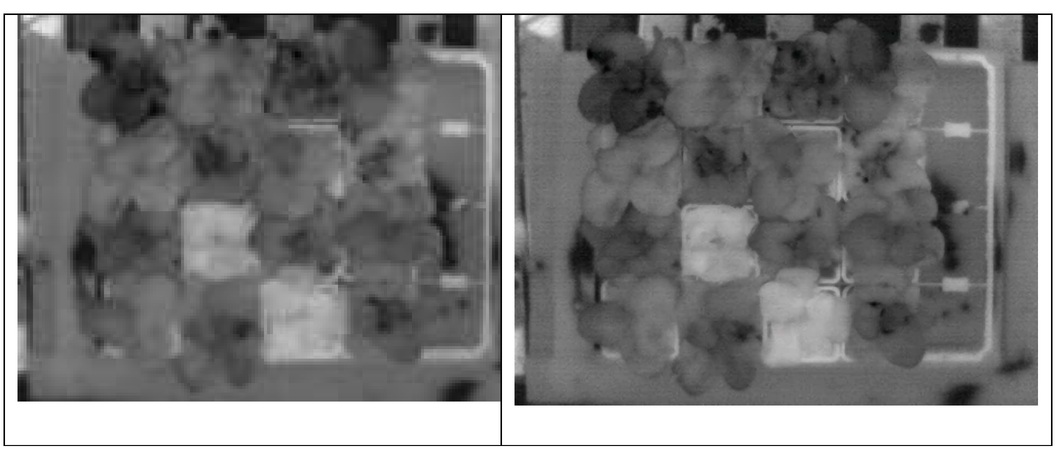


Figure 2: The left hand image is an untreated low-resolution image (320x240) and the right hand image is an enhanced high-resolution image (960x720)

Image registration

The main aim of the project was to develop methods for combining thermal and visual information to improve the interpretation of a crop image. For example, colour information from a visual image can be used to identify different types of plant tissue thus allowing better thermal comparison between comparable tissues on different plants.

Image registration is the process of transforming different sets of data to a single coordinate system. In the case of multisensor registration, the images to be aligned are not necessarily similar, so that appearance-based registration methods cannot be used. It is necessary to use features that are stable with respect to sensor, i.e., the same physical artifact produces features in both images (2).

Since both images are taken from similar viewpoints, the general transform for registration of planar scenes (planar homography) can be approximated by a similarity transform with four parameters:

- scaling (s)
- rotation (α)
- translation (tx, ty)

$$\begin{bmatrix} x_{RGB} \\ y_{RGB} \end{bmatrix} = s \cdot \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \cdot \begin{bmatrix} x_{IR} \\ y_{IR} \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix}$$

For our plant images, we propose using pair of points and corner detection to calculate the registration parameters

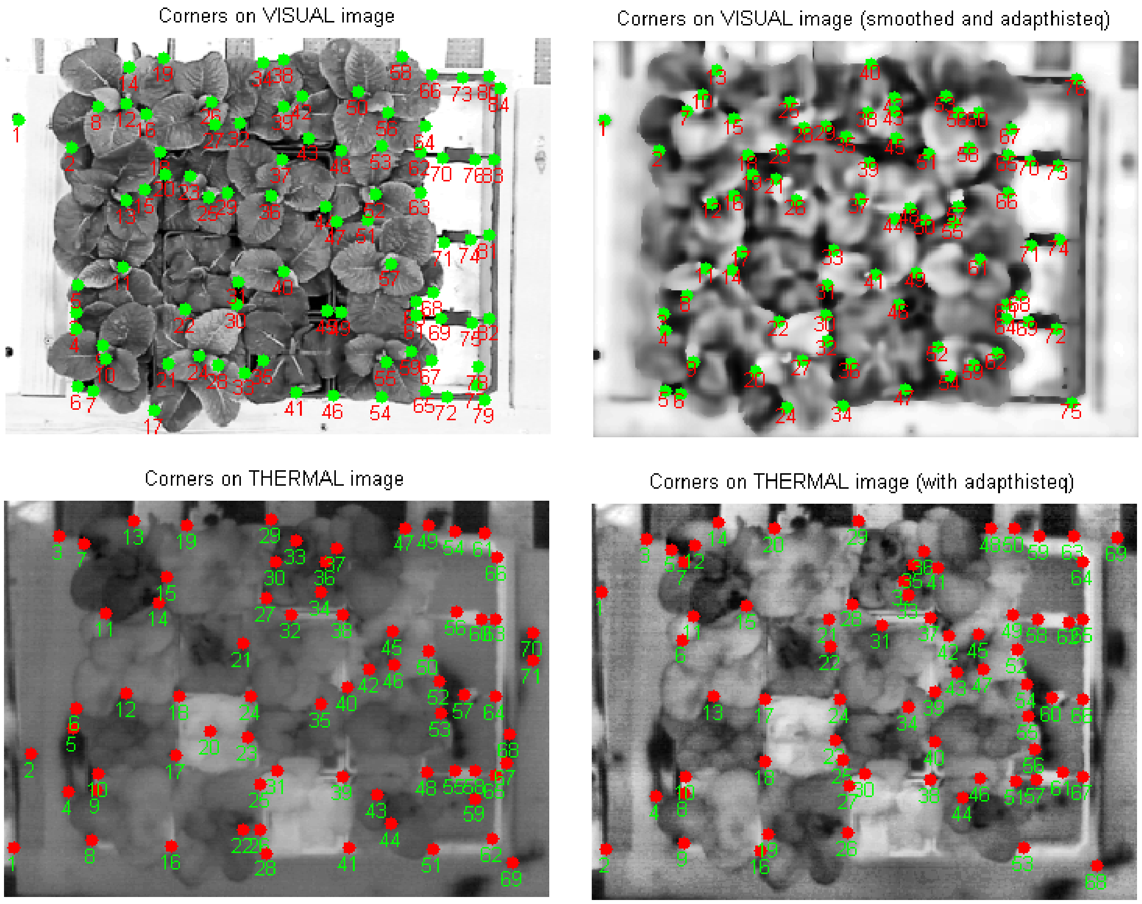


Figure 3: Corner detection on visual and thermal images

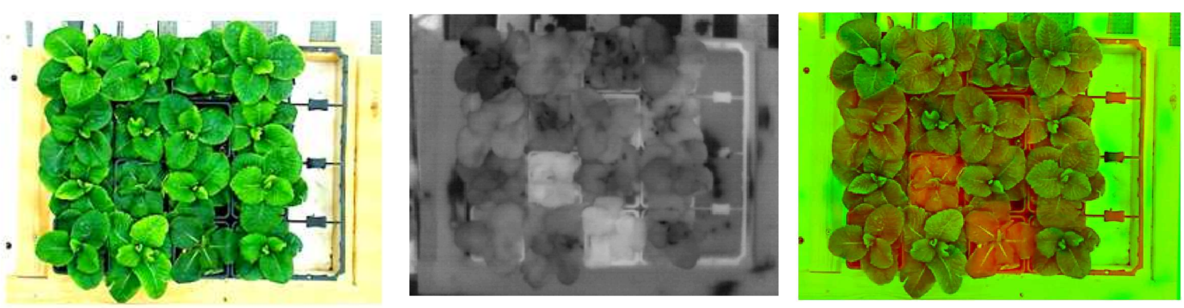
After choosing the best fitting pair of points the estimated transformation parameters for the example were:

alpha = -0.0211

scale = 1.0367

tx = -14.9019

ty = -7.4559



Visual image Thermal image Registration using false colour

Figure 4: Registration of visual and thermal images

Combined thermal and visual models

The next stage following image registration is to combine visual and thermal information into a single model that can be used to precisely compare the temperature profile of the crop. Temperature anomalies would be detected by comparing similar tissues on different plants or different areas of crops so that anomalous temperatures can be detected relative to the expected background crop temperature.

This work would have followed on from the image registration work but had not been started at the time of the project termination.

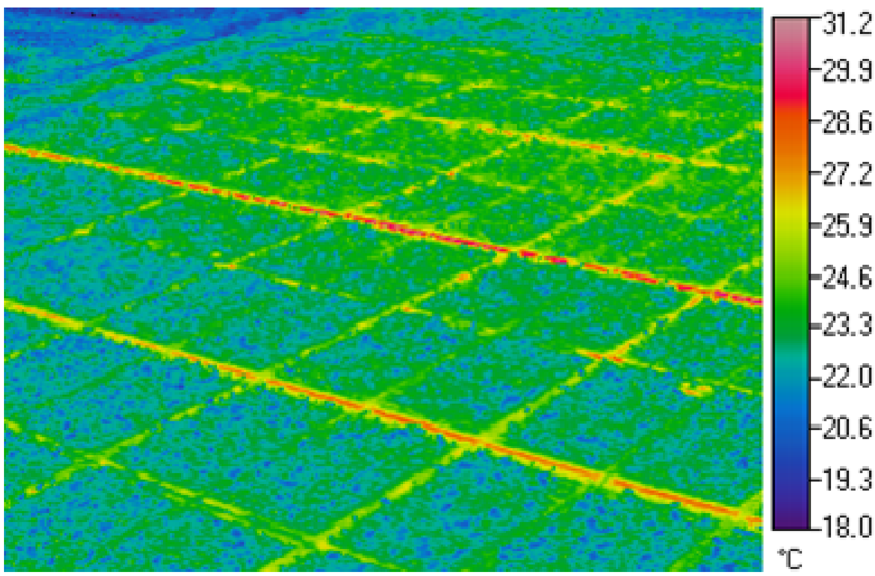
Experimental set-up at WHRI

All experimental images collected at WHRI were vertical images taken at a height of about 1.5 metres above the experimental plants with a high resolution Logitech webcam attached to the thermal camera mount to provide a matching high resolution visual image for each thermal image. The thermal camera imaging system is shown below.

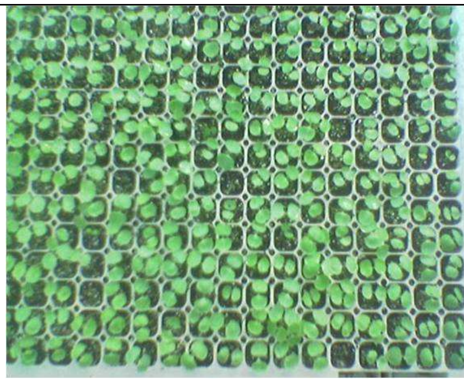
Results and discussion

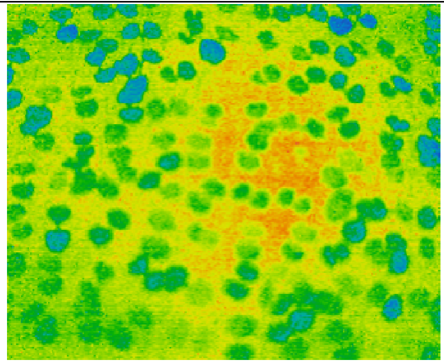
i) Commercial crop scanning

At a preliminary stage in this project, a visit was made to Bordon Hill Nurseries to explore the feasibility of using thermal cameras to measure plant temperature in a commercial environment. The following image shows an oblique false colour thermal image of seedling plants in seed trays at Bordon Hill. Although the image distinguishes macro-features such as tray boundaries and whole trays it is unlikely that anomalies at the individual plant level would be detected at this scale of observation.



The following images show a visual image of a tray of seedlings and a thermal image of part of the same tray (the images do not fully match). The thermal image shows evidence of a warm spot (red) which demonstrates the potential of the thermal camera for detecting thermal anomalies. It was not possible to investigate this anomaly further but the warm spot appears to be associated with the soil surface itself which may suggest an irrigation effect. Note that the thermal plant images in the area of the warm spot are yellower than in the rest of the image which indicates that these plants had a higher temperature than the rest of the crop. This example shows the potential of a thermal camera for detecting temperature anomalies in a crop but also illustrates some of the difficulties of using automated crop scanning for anomalies.



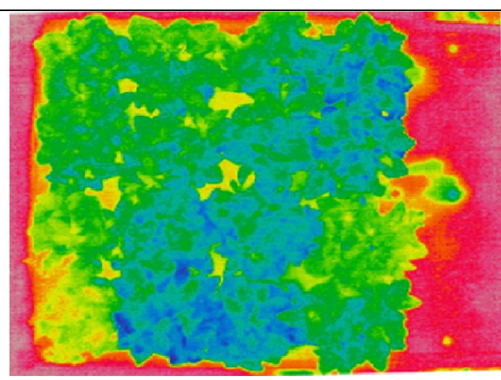


ii) Water stress treatments

The emphasis of the first year of the project was to develop a protocol for collecting and processing thermal images for thermal image analysis. For this purpose, a series of water stress treatments was used to explore the power of thermal imaging for detecting thermal effects due to water stress.

Petunia

The following images show the effects of normal watering (Wet) versus no watering (Dry) on petunia where the actual allocation of watering treatments is shown in the key beneath the images. The image on the left is a visual image of the treated plants and while the image on the right is a false colour thermal image. The visual image shows no evidence of wilting or plant stress but the thermal image shows lower temperature effects (blue) for the watered plants and higher temperature effects (yellow/orange) for the stressed plants. It is important to note that there was also a temperature trend effect across the tray with the plants on the left of the tray warmer, on average, than the plants on the right. For example, the two watered plants at the top left of the image appear to have approximately the same temperature as the two dry plants at the bottom right.



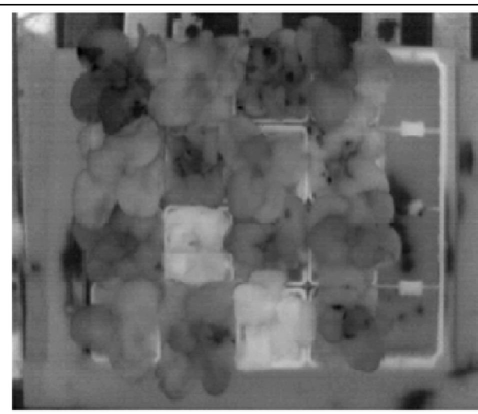
Water stress treatments

Wet	Dry	Dry	Wet
Wet	Dry	Dry	Wet
Dry	Wet	Wet	Dry
Dry	Wet	Wet	Dry

This shows that when using temperature effects to detect plant stress on crops, it will usually be necessary to fit appropriate statistical trend models to adjust for positional effects in the bed. After removing bed trend effects and positional effects, temperature differences between plants in the same bed can be compared on the basis of plant stress effects alone.

Primula

The following images show the effects of normal watering (Wet) versus no watering (Dry) on primula where the actual allocation of watering treatments is shown in the key beneath the two images. The image on the left is a visual image of the treated plants while the image on the right is a grayscale thermal image where the darker shades indicate cooler temperatures and the lighter shades indicate warmer temperatures. The grayscale thermal image has only limited resolution but it is possible to distinguish individual plants and individual leaves. The watering treatments were applied in a checkerboard pattern and the stressed plants are clearly identified by their lighter shade in the first three columns of the array although the pattern is less obvious in the final column.



Water stress treatments

Wet	Dry	Wet	Dry
Dry	Wet	Dry	Wet

Wet	Dry	Wet	Dry
Dry	Wet	Dry	Wet

Examination of the individual plants in the grayscale image shows that some of the well watered (wet) plants appear to have different temperatures for different leaves with younger leaves appearing to be cooler than older leaves. This would be consistent with higher transpiration rates from the younger more exposed leaves. The next stage of the analysis would be to match the visual and the thermal images together so that individual plant structures can be identified and the expected temperature of each leaf matched against the corresponding leaves on other plants. This would provide the best possible discrimination for detecting temperature anomalies at the individual leaf level but this work had not been done at the time the project was terminated.

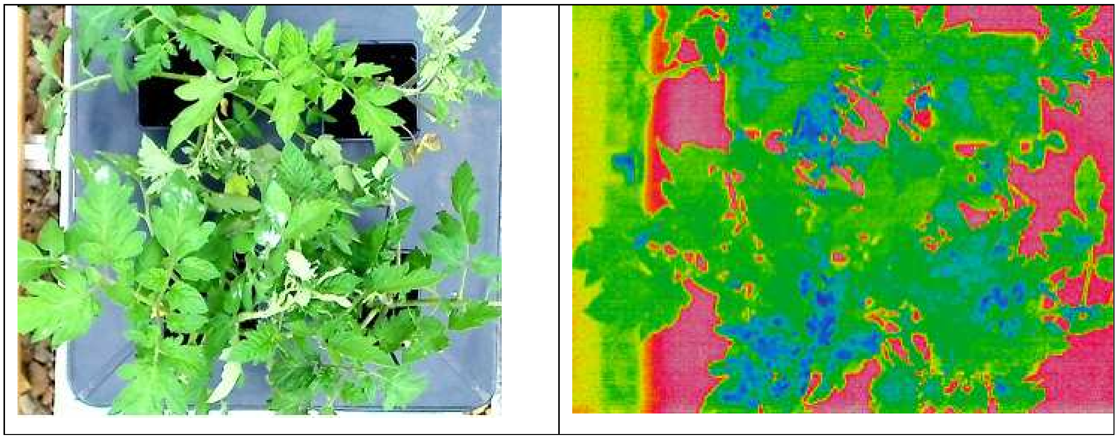
iii) Verticillium wilt treatments

In collaboration with Dr Dez Barbara at WHRI, an experiment was initiated to examine the effect of verticillium wilt treatments on the thermal image of young tomato plants. 24 seven day old tomato seedlings were inoculated with verticillium using two different methods (dip or drench with 12 plants per method) and 12 untreated seedlings were used as controls. Verticillium should be an ideal disease for detection by thermal imaging as it causes wilting due to reduced transpiration but unfortunately, although ample time was given for the disease to develop, there was no evidence of the disease in the plants even after several weeks. Therefore the experiment had to be abandoned without any useful information about the use of thermal imaging for early detection of verticillium.

iv) Tomato powdery mildew

Following the tomato verticillium experiment, Sacha White (HDC student) donated a number of spare tomato plants from his project on powdery mildew (Oidium neolycopersici) on tomato. Although not an ideal disease for early detection by thermal imaging, it was decided to thermally image these plants to look for evidence of disease effects.

The two images shown below are a visual image of tomato plants with visual symptoms of mildew and a matching thermal image taken at the same time.



There is significant temperature variation across the diseased plants including a number of 'cool regions' (blue) but these do not seem to be associated with the disease symptoms. However the images were not collected as part of a planned experiment and it is not possible to reach definitive conclusions from a single pair of images. Nevertheless, the images do illustrate clearly the need for precise visual and thermal image matching to help identify and explain the causes of temperature anomalies.

Conclusions

The project was terminated early and the important work on thermal crop modeling was not done. Nevertheless the early work was promising and showed that the use of combined thermal and visual imaging could be valuable for monitoring crop health. The work will be continued under CP 60a later in 2010.

We have shown that water stress effects can be routinely observed under suitable conditions but due to lack of suitable diseased plant material we have not yet been able to demonstrate thermal effects due to pests and diseases. However, we are confident that under suitable conditions, it should prove feasible to detect disease effects where these effects involve significantly reduced plant transpiration rates.

Technology transfer

R.N. Edmondson, **Crop scanning and image analysis**, HDC Workshop, Warwick HRI 17th February 2010

References

1) M. Irani and S. Peleg, "**Super Resolution From Image Sequences**", ICPR, 2:115--120, June 1990.

2) Tomislav Hrkac, Zoran Kalafatic, Josip Krapac: **Infrared-Visual Image Registration Based on Corners and Hausdorff Distance.** 383-392: Image Analysis, 15th Scandinavian Conference, SCIA 2007, Aalborg, Denmark, June 10-14, 2007, Proceedings. Lecture Notes in Computer Science 4522 Springer 2007, ISBN 978-3-540-73039-2