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Registration of thermal and visible light images of diseased plants using silhouette extraction in the wavelet domain

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ABSTRACT

The joint analysis of thermal and visible light images of plants can help to increase the accuracy of early disease detection. Registration of thermal and visible light images is an important pre-processing operation to perform this joint analysis correctly. In the case of diseased plants, registration using common methods based on mutual information is particularly challenging since the plant texture in the thermal image significantly differs from the corresponding texture in the visible light image. Registration methods based on silhouette extraction are therefore more appropriate. This paper proposes an algorithm for registration of thermal and visible light images of diseased plants based on silhouette extraction. The algorithm is based on a novel multi-scale method that employs the stationary wavelet transform to extract the silhouette of diseased plants in thermal images, in which common gradient-based methods usually fail due to the high noise content. Experimental results show that silhouettes extracted using this method can be used to register thermal and visible light images with high accuracy.

1. Introduction

Thermal imaging may assist in early detection of disease and stress in plants and canopies and thus, allow for the design of timely control treatments [1,2]. Various studies show that the temperature information captured in thermal images of plants may be affected by several factors such as the amount of incident sunlight, the leaf angles and the distance between the thermal camera and the plant [3,4]. Information about the effect of these factors can be obtained by using a stereo visual and thermal imaging setup [5,6]. Therefore, early disease detection accuracy may be increased by performing a joint analysis of temperature data from thermal images and imaging data from visible light images [7–9]. Thermal and visible light images are usually captured using different types of sensors from different viewpoints and with different resolutions. As a pre-processing step before joint analysis, thermal and visible light images of plants must be aligned so that the pixel locations in both images correspond to the same physical locations in the plant.

To the best of our knowledge, there is no existing literature on automatic registration of thermal and visible light images of *diseased* plants. However, in the past researchers have *manually* registered thermal and colour images for multi-modal image analysis of plants [8]. Automatic registration of thermal and visible images of diseased plants is a challenging task due to the fact that there is a mismatch in texture information and edge information is often missing in the corresponding visible/thermal image. The reason for this information mismatch is that the thermal profile of a leaf in a diseased plant can show symptoms of disease before they visibly appear. In other words, a leaf with a smooth green profile (colour) in the visible light image may have a textured profile in the thermal image with a temperature higher or lower compared to that of the surrounding environment because of the changes in the plant which visibly appear at a later stage.

Infrared thermal imaging has been previously employed in video surveillance e.g., traffic, airport security, detection of concealed weapons, smoke detection and patient monitoring [4,10–12]. One approach for registration is to calibrate the stereo visual + thermal imaging camera setup and use transformations to align the resulting images [13–15]. One disadvantage of this approach is that the calibration parameters of the cameras may not be readily available. In such cases, a possible solution is to align the thermal and visible

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light images using exclusively image based information. Various researchers have proposed methods that use line, edge and gradient information to register thermal and visible images of scenes with strong edge and gradient information [16–19]. In general, line, edge and corner based methods are reliable for images of man-made environments, however they perform poorly on images of natural objects. Jarc et al. [20] proposed a registration method based on texture features; however, the method is not automatic and requires manual selection of features. Other methods based on mutual information and cross correlation of image patches rely on texture similarities between the two kinds of images [15,19,21]. Since there is a high probability that texture information may be missing in the corresponding visible/thermal image(s) of diseased plants, methods based on mutual information and cross-correlation may not be a good choice for registration.

Region-based methods, such as those based on silhouette extraction, usually provide more reliable correspondence between visible and thermal images than feature based methods [11,21,22]. Bilodeau et al. [21] proposed registering thermal and visible images of people by extracting features from human silhouettes. Torabi et al. [23] suggested a RANSAC trajectory-to-trajectory matching based registration method that maximizes human silhouette overlap in video sequences. Han et al. [12] proposed a hierarchical genetic algorithm (HGA) for silhouette extraction using an automatic registration method for human movement detection. The authors improve the accuracy of the extracted human silhouette by combining silhouette and thermal/colour information from coarsely registered thermal and visible images. Human body temperature is generally higher than that of the background region and this characteristic has been used by researchers in [11,22] to extract human silhouettes. However, in the case of thermal images of diseased plants, the temperature profile does not exhibit this characteristic. It is possible that within the same plant the temperature of different regions is higher or lower than that of the background. Another common method for silhouette extraction in video sequences is background subtraction. This method usually provides very good results because of the high frame rate of the sequences and the fact that the background between two consecutive frames is usually very similar. For the case of images of diseased plants, background subtraction is not efficient due to the limited number of consecutive still images and the fact that there may be a large interval between two consecutive still images.

In this paper, we propose an algorithm for registration of thermal and visible light images of diseased plants based on silhouette registration. The algorithm features a novel multi-scale method for silhouette extraction of plants in thermal images. An overview of the proposed algorithm is shown in Fig. 1. For the visible light images, the algorithm uses the strength of edges/gradient to detect and extract the silhouette whereas for the thermal images it uses a method based on the stationary wavelet transform (SWT). The latter follows a multi-scale approach that first estimates of the silhouette at coarse scales by using the curvature strength as computed from the Hessian matrix of coefficients at each pixel location. It then uses these estimates to refine the silhouette at finer scales. After silhouette extraction, the algorithm employs a rigid + non-rigid registration method based on the non-rigid method proposed by Rueckert et al. [24] to register the thermal and visible light images. The remainder of the paper is organised as follows. Section 2 describes the image acquisition process. Section 3 presents the proposed SWT-based method. Section 4 describes the rigid+non-rigid registration method and Section 5 presents the experimental results.

2. Image acquisition

An experimental setup was designed and developed at the Department of Computer Science, University of Warwick, UK, to simultaneously acquire visual and thermal images of diseased/healthy plants. The setup consisted of two visible light imaging cameras *Canon Powershot S100*, and a thermal imaging camera *Cedip Titanium*. The setup was used to image tomato plants infected with the fungus *Oidium neolycopersici* which causes powdery mildew disease. 10^6 conidia/ml and various control treatments were applied which resulted in different amounts of disease developments made available for the imaging. The disease symptoms consist of white powdery spots (first appearing after approximately, 7 days) that expand over time and eventually cause chlorosis and leaf die-back. Thermal and visible light images of 71 plants under 10 different treatments were captured for 14 days (4 October 2012 to 17 October 2012) in a controlled environment at 20 °C.

3. Silhouette extraction

3.1. Thermal image

Extraction of plant silhouettes from thermal images obtained in our experiments is a difficult step because of high noise content, and thus common methods based on gradient information usually fail. Since thermal images were obtained from diseased plants inoculated with powdery mildew, the intensity of the thermal profile changes within leaves. Fig. 2(c) shows an enhanced (by truncating the lower and upper 1% of pixel values and by contrast stretching) thermal image of a diseased plant where the thermal profile (i.e., intensity) of the background is very close to that of the leaves. Furthermore, the thermal profile of some of the leaves is higher/lower than that of the background. Because of the presence of weak edges in the thermal image of the diseased plant, edge detection methods such as gradient, Canny edge detector, difference of Gaussian, and Laplacian perform poorly on thermal images. Based on this observation, we propose an approach that is minimally affected by within leaf intensity changes.

It has been shown that the joint statistics of coefficients obtained after wavelet transformation (WT) show strong correlation among object boundaries in thermal and visible light images [25]. Thermal images, therefore, capture most of the object boundaries and thus can be used to extract silhouettes. Additionally, WT has shown to be

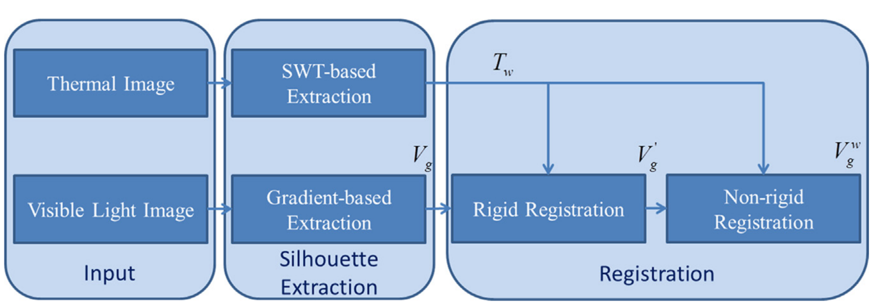

Fig. 1. Overview of the proposed algorithm.