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Photometric stereo for three-dimensional leaf venation extraction

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ABSTRACT

Leaf venation extraction studies have been strongly discouraged by considerable challenges posed by venation architectures that are complex, diverse and subtle. Additionally, unpredictable local leaf curvatures, undesirable ambient illuminations, and abnormal conditions of leaves may coexist with other complications. While leaf venation extraction has high potential for assisting with plant phenotyping, speciation and modelling, its investigations to date have been confined to colour image acquisition and processing which are commonly confounded by the aforementioned biotic and abiotic variations. To bridge the gaps in this area, we have designed a 3D imaging system for leaf venation extraction, which can overcome dark or bright ambient illumination and can allow for 3D data reconstruction in high resolution. We further propose a novel leaf venation extraction algorithm that can obtain illumination-independent surface normal features by performing Photometric Stereo reconstruction as well as local shape measures by fusing the decoupled shape index and curvedness features. In addition, this algorithm can determine venation polarity – whether veins are raised above or recessed into a leaf. Tests on both sides of different leaf species with varied venation architectures show that the proposed method is accurate in extracting the primary, secondary and even tertiary veins. It also proves to be robust against leaf diseases which can cause dramatic changes in colour. The effectiveness of this algorithm in determining venation polarity is verified by it correctly recognising raised or recessed veins in nine different experiments.

1. Introduction

Leaf venation is the patterned veins in the blade of a leaf. Leaf veins are considered to be related to resource delivery rates and photosynthetic capacity, but their high potential is undervalued and studies are limited [1]. Nelson in 1997 pointed out that the underlying mechanisms for leaf vascularisation were poorly understood and most studies were descriptive [2]. A few years later, computer vision studies centred on leaf venation extraction grew and developed, offering a transformative opportunity for quantitatively analysing leaf venation architectures [3]. Although this branch of computer vision studies is still at its youth, a few studies have shown that leaf venation extraction can greatly benefit plant speciation [4], phenotyping [5], as well as measuring physiological properties of plants (e.g. water transport and flow velocity in leaves [6]). It can even be of evolutionary significance by being able to reveal gene induced traits [7,8].

However, in this emerging field, there has been limited work due to the considerable challenges, e.g. subtle vein structures that commonly have diameters less than one millimetre, complex vascularisation of veins, and other variations caused by biotic or abiotic stress and/or ambient lighting. Leaf venation architectures are very distinctive. Common venation types include *palmate venation* where primary veins radiate from the petiole, *pinnate venation* where secondary veins branch from a primary vein, *transverse venation* (or cross-venulate) where tertiary veins connect secondary veins, and *reticulated venation* where veins are net-like. Although leaves are extremely diverse in venation architecture, their venation systems commonly share two primary

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traits. Without explaining biological causes, these two traits can be summarised as:

1) Colour. Leaf veins and mesophyll have a certain level of difference in colour due to their varied reflectance properties. This can be characterised in images as edges and corners.
2) Topography. Leaf veins can appear to be ridge-like or rut-like structures relative to a leaf blade that is mostly locally flat.

While leaf veins can be a source of edges and corners in colour or greyscale leaf images, more edges may be caused by numerous factors including ambient illumination, local leaf curvatures, colour patterns of a leaf, leaf diseases, etc. In the rest of the paper, we refer to the former (leaf vein edges) as *true edges* and the latter as *false edges*. We also define the polarity of leaf venation according to whether they form ridges or ruts on a leaf blade – *positive* for ridge-like veins and *negative* for rut-like veins. It should be noted that, as each leaf has two sides (upper and lower epidermis), our definition of venation polarity is specific to either the upper side or the lower side of a leaf. For example, leaf venation can be negative on the upper side of a leaf, but positive on the lower side.

Regarding leaf venation architectures, differences in individuals and across species are so significant that they cannot be well characterised by image colour or intensity based features alone. Apart from inherent variations that pose great challenges to leaf venation extraction, environmental factors further magnify this by causing complications such as leaf dehydration, powdery mildew, leaf curl, leaf mottling, etc. Investigations of these different traits [9] in laboratory environments often enforce sufficient and homogeneous lighting to avoid presence of severe shadows and specularities. However, in real-world environments, shadows and specularities are commonly inevitable while undesirable illumination can also cause images to be underexposed or overexposed. Therefore, we propose a 3D leaf imaging system and a leaf venation extraction algorithm and we make the following contributions:

1) The proposed 3D leaf imaging system is capable of recovering illumination-independent and high-resolution surface normal (3D) features of leaves.
2) The proposed leaf venation extraction algorithm is fully compatible with the hardware system. It employs 3D features to realise wide applicability, high accuracy and robustness. It can also detect leaf vein polarity.
3) The proposed method can overcome undesirable variations commonly found in real-world environments such as illumination changes and abnormalities induced by leaf diseases.

2. Related work

In the last two decades, researchers have been attempting to resolve the leaf venation extraction problem by utilising different types of features in colour or greyscale images. We review in this section a number of representative methods and give an indication of the current research state as well as challenges being faced with and gaps to be bridged.

In 2003, [10] introduced a two-stage approach where intensity histogram information is initially used to filter out most background pixels. Gradient features representing edges which are further described by local contrast are combined with five statistical features based on intensity values. These features extracted from image regions are then used to train a neural network to achieve automatic classification of vein and non-vein pixels. The results showed that this method only achieved slightly better performance than using a Sobel filter [11]. Similar to this method, many others researchers also intuitively based their methods on edge features. For example, [12] proposed a leaf vein extraction method based on the active contour model. The active contour model [13], i.e. snakes, is widely used for image segmentation and edge detection, but it requires prior knowledge of desired contour shapes, i.e. characterised leaf vein structures in this case. Consequently, their method enforces definition of leaf vein geometries by comparing pixel colour and measuring pixel distance in the HSI colour space [14]. Due to these assumed characteristics of leaf venation, this method can only deal with a specific type of leaf venation architecture, and a high noise (non-vein pixels) level is still present in their demonstration of results. [15] investigated vein morphologies in greyscale images transformed in the HSV colour space. Morphological erosion and dilation, along with top-hat [16] and bottom-hat transformations, are employed by this method to obtain leaf venation. Disconnected vein segments are then jointed and isolated pixels removed. As their experiments were conducted on scanned leaf images (by a HP Scanjet 4070 photosmart scanner) where local leaf curvatures were flattened and illumination was near to ideal, this method would very likely suffer in dealing with leaf data captured in dynamic ambient environments.

A few other methods distinguish themselves by employing supervised or unsupervised learning methods to extract and process edge features differently. For example, [17] proposed to combine Sobel edges with an artificial neural network for leaf venation extraction. This method assumes that vein pixels are relatively darker than neighbouring pixels and extracts those around Sobel edges by comparing their first and second order derivatives. [18] presented a venation extraction method based on Independent Component Analysis to learn latent independent causes of leaf features by considering them as a set of linear basis functions. Results show that this method can detect primary and secondary veins of pinnate venations while tertiary veins will likely become noise.

As opposed to characterising leaf veins as edges, [19] considered them as ridges. In their work, the Hessian matrix for each pixel is calculated, which essentially consists of second-order derivatives of intensity values. This differs from many edge detection based methods by considering leaf veins as ridges instead of edges. By comparing the two Eigen values of a Hessian matrix, the local shape around each pixel can be quantified.

Recently, research works started to show how leaf venation could benefit plant speciation and suggested that this would further demand higher robustness against colour changes induced by factors such as diseases and nutritional deficiency. [20] proved the effectiveness of leaf venation combined with other features for plant recognition by achieving a recognition accuracy of 97.1% on a dataset with 1907 leaf images of 32 species. As they only employed basic morphological operations (i.e. erosion followed by dilation), only the primary vein and its direction could be determined. Its inherent limitations also mean that the venation extraction method cannot distinguish between true and false edges. [21] found that venation extraction on apple-tree leaves can, apart from benefiting plant recognition and plant growth analysis, assist with detection and localisation of discoloured leaf regions with different sizes and intensities, e.g. brown spots in the presence of hydrogen peroxide and plant peroxidases. The technique used for venation extraction is based on stepwise vein tracking at local image regions, which minimises a cost function designed for the pinnate venation architecture. As a result, it only tracks primary and secondary veins that are subject to a specific morphology and that do not change angle rapidly. Although this increases its robustness against image noise and leaf discolouration, this technique cannot be generalised for venation extraction of a variety of plant species and venation architectures. [22] pointed out that nutrition