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Image Analysis Applications in Plant Growth and Health Assessment

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Abstract

Image analysis systems have been increasingly utilized for the assessment of plant growth and health for decades. This study reviews recent developments in image analysis systems for the plant growth and health evaluation. Furthermore, plant disease detection, pest detection and identification, IR thermography, aerial infrared photography, plant and plant part identification, plant discrimination, robotic harvesting, yield estimation and detection of the fruit maturity by image analysis systems are evaluated in this paper. More specifically, feature parameters like size, shape and colour of the fruits are used to detect the object (fruit) in the plant image and to assess the growth and health by image processing. Then, the advantages of image analysis systems for the plant growth and health evaluation are demonstrated. In addition, some points to simplify the implementation of image analysis systems for plant growth and health evaluation are also investigated and discussed. At the end of the introduction part, summary table including the process able plant parameters by image analysis techniques used in obtaining the plant information are presented with related reference.

Key words: Image analysis, assessment methods, plant growth, plant health

Bitki Büyüme ve Sağlığının Değerlendirilmesinde Görüntü Analizi Uygulamaları

Özet

Son yıllarda bitki büyüme ve sağlığının değerlendirilmesi için görüntü analiz sistemleri yoğun olarak kullanılmaktadır. Bu çalışma bitki büyüme ve sağlığının değerlendirilmesi için kullanılan görüntü analiz sistemlerindeki son gelişmeleri değerlendirmektedir. Ayrıca, bu yayında bitki hastalıklarının tespiti, zararlı tespiti ve tanımlaması, infrared termografi, infrared fotografi, bitki ve bitki kısımlarının tanımlanması, bitkilerin ayırt edilmesi, robotik hasat, verim tahmini ve görüntü analiz sistemleri ile meyvelerin olgunluk tespiti değerlendiririlmiştir. Daha spesifik olarak, bitki fotoğrafı içindeki objenin (meyvenin) tespit edilmesi için boyut, şekil ve renk gibi meyveye ait özellik parametreleri kullanılmış ve görüntü işleme ile bitkinin büyüme ve sağlığı değerlendirilmiştir. Daha sonra, bitki büyüme ve sağlığını değerlendirmek için kullanılan görüntü analiz sistemlerinin avantajları ortaya konmuştur. Buna ek olarak bitki büyüme ve sağlığını değerlendirmek için kullanılan görüntü analiz sistemlerinin uygulanabilirliğini kolaylaştırmak amacıyla tekrar çözümlenmesi gereken bazı noktalar tartışılmıştır. Giriş bölümünün sonunda ise referanslar ile birlikte, görüntü analizi ile işlenebilen bitki parametreleri ve bitkilere ait bilgileri elde etmede kullanılan görüntü işleme tekniklerini içeren özet tablo sunulmuştur.

Anahtar kelimeler: Görüntü analizi, değerlendirme metotları, bitki büyümesi, bitki sağlığı

Introduction

In biological studies, plant growth and health assessments are still evaluated manually by human observations, which are time consuming and destructive. Because of this there is an increasing demand for objectivity and efficiency. Thus, automatic image analysis technique has become a useful tool in biological researches. Image analysis method is a non-invasive and non-destructive sensing system. It can be used to extract and quantify different kinds of information like size, shape, colour, and moisture and growth rate of a targeted object.

This paper presents recent developments of image analysis applications in plant growth and health assessment. Almost all monitoring systems using image analysis techniques involves seven basic steps like image recording, pre-processing, image segmentation, detection, extraction, classification and finally validation. Examples of image monitoring application includes satellite image analysis, aerial photographs and video graphs, 3D images, acoustic images, MR images and images in electron microscopy (Nilsson, 2009).

Image analysis systems have a great potential in the assessment of plant growth and health with high accuracy (Du and Sun, 2004). The automatic image analysis systems offer flexibility in application. To develop an automatic monitoring tool for the plant growth and health assessment, image analysis is usually integrated into the mechanical devices to replace manual assessments by humans (Du and Sun, 2004). The image analysis system is used to control the operation of the machinery. There are five main steps in image analysis, including: image recordings, pre-analysing, segmentation, detection and classification (Du and Sun, 2004).

Image processing can reduce the total information of plant image to a manageable amount, by increasing edges and making geometrical corrections, before the analysis of measurements and identification of some specific details such as size, area and shape (Nilsson, 2009). The biggest benefit of image analysis is that it can view specific areas and contrast colours. This allows visual explication and interactive analysis by the computer. The analysed images can also be stored in a mass memory. When a PC is bonded to a net, it is very easy to transfer data among scientists from different cities or countries (Nilsson, 2009).

The objective of this study was to review current image processing techniques to assess the plant growth and health. Furthermore, the role of the image analysis systems in the plant growth and health was explained. Applications and models developed using image analysis techniques for plant growth and health assessment and some remarks on their results can be seen in Table 1.

Table 1. Applications and models developed using image analysis techniques and some remarks on their results

References	Objective of the study	Method	Result
Parrish and Goksel, 1977	To automatic fruit harvesting	Pictorial pattern recognition	Results were found as satisfactory
Otsu, 1979	Automatic threshold selection for picture segmentation	Nonparametric method	Method had desirable advantages for threshold selection
Eguchi et al., 1983.	To evaluate plant growth	Digital image processing technique	Usable to measure plant growth in red and infra-red region.
Oneo et al., 1983	To measure annual rings of a living tree	Computed tomography	Useful not only for plants and trees but also for archaeology
Hashimoto et al.,	To measure temperatures	Infrared scanning technology	Useful for monitoring short

1984	of leafs		term temperature changes on leaves
Omasa et al., 1985	To measure root system and water content of soil	Computed tomography, NMR	Method was found as useful to measure root system and water content of soil
Bottomley et al., 1986	To investigate plant root systems and water	NMR technology	NMR technology was found as an effective tool
Meyer and Davison, 1987	To collect data of different growth response of the plant	Image analysis	System was found usable
Slaughter and Harrel, 1987	To differentiate citrus fruit from background leaves	Color vision	Provided a satisfactory means
Whittaker et al., 1987	To detect location of tomatoes	Digital image processing	The location of tomatoes was successfully detected
Meyer et al., 1988	To detect crop residue on soil surface	A spectral analysis	System detected crop residue
Sites and Delwiche, 1988	To identify fruits	Computer vision for robotic harvesting	Fruits were detected with 89% accuracy
Batchelor and Searcy, 1989	To determine stem-root joint on carrots	Computer vision technology	Developed algorithms can estimate stem-root joint of carrots
Ewing and Horton, 1999	To get some quantitative information from colour images	Image processing	Conopy of cover measured from the color photographs successfully
Hack, 1989	To measure of plant growth in the greenhouse	Image processing with Ccd camera and electronic balance	Image processing provided successful leaf area measurement
Twidwell et al., 1989	To detect plant tissue	Image processing	It is not efficient
Han and Hayes, 1990	To detect soil cover	Image analysis	The method can measure soil cover with less human error
Tarbell and Reid, 1991	To detect growth rate of corn	An image-based monitoring system	64 to 320 attributes were obtained for each plant
Blazquez, 1989	To measure stress and growth of citrus trees	Image analysis with infrared photographs	Aerial colour infrared photographs were found as a good
Humphries and Simonton, 1993	To define geranium cutting properties	RGB method	Pixel classification was found successful between 93 and 97%
Choi et al., 1995	To classify fresh tomatoes from the sixth maturity stages	Colour image analyses	The proposed system provides 77% success to classify tested tomatoes
Shimizu and Heins, 1995	To check plant growth	Digital camera	The method was successful for interim age differences
Vanhenten and Bontsema, 1995	Non-destructive measurement for crop growth	Image processing	The method was useful for non-destructive measurements
Bignami and Rossini, 1996	To estimate leaf area index and plant size	Image processing technology	Lai and plant size parameters were successfully estimated
Ling and Ruzhitsky, 1996	To identify the canopy level of tomato seedlings	Machine vision	The system defined the canopy level of tomato seedlings
Ling et al., 1995	Monitoring of plant growth	Machine vision	Plant growth was monitored efficiently
Tucker and Chakraborty, 1997	To identify leaf diseases	Ccd-camera, image processing	A new tool was developed to detect leaf disease
Schmundt et al., 1998	To quantify leaf growth	Image sequence analysis	The method was successful for mapping the responses
Leister et al., 1999	To analyse plant growth	Image processing	The growth rate was

	and performance		accurately determined
Horgan et al., 2001	For discrimination of carrot cultivars	Automatic, objective image analysis	Image analytic techniques helped for recognition carrot
Kacira and Ling, 2001	To analyze plant growth and health	Image monitoring with infrared thermometry	The method was useful to collect needed data
Wang et al., 2001	For genetic analysis	Computer vision analysis	The method can useful for the virtual architectures of
Kacira et al., 2002	To extract plant features	image–processing technique	Plant water stress detection was feasible with proposed method
Li et al., 2002	To detect apple surface defects	Computer image method	Developed method was practical and useful.
Philipp and Rath, 2002	To separate plants	RGB colour analysis	The most effective method was logarithmic seperation
Aitkenhead et al., 2003	To discriminate crop seedlings from weeds	Image analysis and artificial intelligence	Neural network-based methodology was useful to use it.
Herold et al., 2005	Monitoring of apple growth on the tree	Spectrophotometric module	The system has a big potential for non-destructive fruit growth monitoring
Baker et al., 1996	To predict leaf area and dimentions	Image processing (using digital camera and computer)	The proposed system provide a reliable prediction of leaf area
Cho et al., 2007	To identify some pests in greenhouse	Image processing technology	50 adult insects were determined by using developed methods
Kavdir and Guyer, 2008	For apple sorting	Neural network	System was successful for apple sorting
Nilsson, 2009	To detect plant diseases and pathogens	Remote sensing and image analysis	Density of disease was detected but specific diseases could not identified
Cohen et al., 2010	To estimate number of fruits in orchards	Image processing	The proposed system was found more than 85% of successful
Al-Hiary et al., 2011	To automatic identification plant leaf diseases	Image processing using green and red pixels	The proposed system can detect leaf diseases
Yang et al., 2011	To count the number of pests	Motion estimation, multiple-frame verification	The developed model was more efficient to detect moving pests
Islam et al., 2012	Automatic disease detection	Computer vision based recognition system	It has a more precise classification rate than neural network
Arivazhagan et al., 2013	Plant leaf detection	Image processing	The system can identify diseases with 94% accuracy
Bhadane et al., 2013	Early pest detection	Image processing	Infection of leaves were detected.
Kanjalkar and Lokhande, 2013	Automatic detection of plant leaf diseases	Ann classification is computed by giving different features	Different leaf diseases were accurately classified
Krishnan and Jabert, 2013	Automated pest detection	Image analysis	Pest infected areas were identified
Kutty et al., 2013	To detect watermelon leaf diseases	Image processing with RGB	75.9% of leaf diseases were detected
Payne et al., 2013	To count mangos on tree	Image analysis – segmentation	The system was efficient with less fruit
Thulasipriya et al., 2013	Monitoring of pest insect traps	Image processing, color space transformation, fruit fly recognition	The system was useful for the insect count and not controlling
Rupesh et al., 2013	Pest identification in	Machine vision and digital	It has more precision in

	greenhouse	image processing	identifying the presence of pest at early stage
Sanjay and Nitin, 2013	To detect leaf diseases	Vision analysis	The recognition rate of classification process needs to be increased
Takahashi et al., 2013	To find the effects of storage duration and temperature	Chromaticity by image analysis	The system was useful to find the effects of parameters
Barbedo, 2014	To count whiteflies on The soybean leaves	Digital image processing technology	The system can detect and quantify the nymph stage of whiteflies.
Kandalkar et al., 2014	Plant pest identification and detection	Dwt and back propagation neural networks	Type of pest was identified
Oberti et al., 2014	To identify powdery mildew in grapevine	Multispectral imaging approach	The systems can detect initial foci of grapevine powdery mildew
Payne et al., 2014	To predict mango yield	Image processing	Mango fruits were detected with 78.3%
Prathibha et al., 2014	Early pest detection	Image processing	System can detect the pests in tomato fruit in the early stage.
Intaravanne and Sumriddetch, 2015	To predict the needed fertilizer for rice	Android device and image processing	Leaf colour levels can be accurately identified
Mainkar et al., 2015	To automatically detect plant leaf diseases	Image analysis	Leaf diseases were detected by the proposed system
Miranda et al., 2014	Detection of pests in the field of agriculture	Image analysis method	Pests were successfully detected in the rice fields
Muthukannan et al., 2015	Identification of diseased plant leaf	Neural-network analysis	It can be improved for crop quality
Nyakwende et al., 2015	To measure leaf areas in intact tomato	Image processing	System performance was acceptable
Rastogi et al., 2015	To identify leaf diseases	Image monitoring and fuzzy-logic	Method can be used instead of the manual leaf identification
Tripathi and Save, 2015	To identify leaf diseases	Image analysis and neural network technique	An efficient, simple, fully automatic, cheap, fast and reliable system
Vesali et al., 2015	To predict the corn leaves chlorophyll	Smartphone's camera	It is useful and a low cost alternative
Zhou et al., 2015	To detect wheat resistance	Digital RGB images	Monitoring system was successful
Gopal, 2016	To develop an auto-irrigation and pest detection system	Image processing	Developed model was useful for irrigation and pest detection
Hanson et al., 2016	For detection and identification of plant disease	Image processing, neural networks	Watermelon leaf diseases were detected with 75.9% of accuracy
Zhao et al., 2016	T predict oriental fruit moths	Digital image processing technology	Developed system was successful for prediction (0.99, $p < 0.05$).
Maharlooei et al., 2017	To detect and count different sized soybean aphids on a soybean leaf	E-image processing technique	Images captured with an inexpensive digital camera gave satisfactory results

Plant Growth

In today's technology, image analysis finds itself a great use to monitor and assess plant growth and health. Data collected for this purpose allows creating or increasing the performance of the health and growth models. Studies related to the growth and health of plants is mainly focused on leaf area as a feature parameter (Tarbell and Raid, 1991). Thus, plant leaf area can be used to predict the growth of plants as functions of environmental conditions. Disruptive harvesting of plants by sampling of leaves is the most accurate way to measure the leaf area, but it is not good to make repeated measurements on the same plants or remote measurement of plants. Moreover, the areas of the leaves can be predicted based on the correlations between the area and dimensions of leaf size and shape (Baker, 1996). Nevertheless, these recordings can be boring and time consuming, particularly during periods when leaf area is growing quickly. Non-destructive recordings using vision technology have the potential to provide a reliable prediction of area without harvesting the plants. Leaf areas can be obtained by a video camera and processed with a computer (Baker, 1996). Eguchi et al., (1983) tried to adapt an image analysis system for researches of plant growth. In later years, image processing was used by Meyer and Davidson, (1987) to investigate plant growth, by measuring the leaf area; stem chamber and leaf. They also concluded in their study that system accuracy and applicability can be limited by the camera resolution.

The problem of predicting plants biomass with respect to their growth using vision monitoring techniques was discussed by Evers et al., (1987). Hack, (1989) investigated the relationship between fresh weight of the lettuce plant and the recorded leaf area of it in the greenhouse, by image processing system. To determine the plant fresh weight and transpiration, a weighing scale was used in a hydroponic system. This time, the correlation between fresh weight and leaf area gave the best results with an exponential regression equation and with a determination coefficient (R^2) of 0.90. Special software was developed by Tarbell and Reid, (1991) to scan corn plants images. Plant growth and development could be monitored by this image-based monitoring system. Another simulation model was also developed to detect the leaf area in potato plants (Trooien and Heermann, 1992). They have tested several experimental procedures on the simulated potato canopy where they compared the image processed and measured leaf area.

In another research, for hazelnut plants a high correlation between leaf areas obtained with an area meter and canopy silhouette areas measured with image processing was found by Bignami and Rossini, (1996). Nyakwende et al., (2015) found a correlation between true leaf area of intact tomato plants and areas measured using image analysis. The images were obtained from the plants as top-view, side-view and with an oblique angle. Additionally, they investigated the taut-string boundary which provided information about the compactness of the plants as they grow.

Another system using digital video and image analysis was demonstrated by Leister et al., (1999) to non-destructively define the plant size by measuring plant leaf area. The system provided a non-destructive method to assess the plant growth and growth rates by monitoring and quantifying feature parameters of the plant. In another study, plant growth and health in a controlled environment was continuously monitored by Kacira and Ling, (2001) using a vision monitoring approach. Canopy area is also an important variable concerning plant growth. The canopy area of a plant is certainly commensurate to its dry weight. In addition, the plant growth is also expressly correlated to its dry weight. Measuring plant canopy area, or in other terms plant canopy cover, by the means of image processing can give valuable information for plant growth monitoring.

A pattern recognition algorithm was tested by Han and Hayes, (1990) to distinguish crop canopies from the background soil. In another study, the image classification method was used by Han and Hayes, (1990) with soil colour information. Further models were also studied by Vanhenten and Bontsema, (1995) to find the relationship between the soil coverage of lettuce canopy which is measured by image analysis and its dry weight. It was concluded that the dry weight could predicted with 95% accuracy from the soil coverage.

Ewing and Horton, (1999) developed special algorithm to extract some information from colour images. The software allowed obtaining some data from colour images like photographs of plant canopies. Percent canopy cover could also be measured using this software. Growth rates of plants can also be measured directly using image analysis techniques. The stem length and growth rates were measured by image analysis of Verbena bonariensis L. plant by Shimizu and Heins, (1995). Motion in dynamic image sequences of dicot leaves were analysed by Schmundt et al., (1998). By the developed algorithms growth rate could be measured at less than 1% per hour.

Plant Health

Non-invasive and non-intrusive assessment methods can automatically follow the plants with automatic sensing and controlling skills (Kacira and Ling, 2001). Conventional methods used to evaluate plant growth and health is often destructive and requires contact measurements (Kacira and Ling, 2001). For example, to measure soil water potential with a densitometer, it needs to contact with the soil. This kind of measurements cannot be useful for real-time analysis and controlling of plant growth and health. Thus, non-invasive and non-intrusive sensing techniques should be developed to replace conventional methods (Kacira and Ling, 2001). This can be done by the use of image processing techniques together with other remote sensing methods such as aerial infrared photography, nuclear magnetic resonance imaging, radar and microwave. Kanemasu et al., (1985) examined the potential benefits of using remotely sensed data to assess crop response to soil water deficits. He found out that canopy temperature offered a means of assessing critical soil water deficits. Canopy reflectance was useful in estimating canopy parameters like leaf area index (LAI). Critical levels of soil water deficit and LAI played key roles in crop growth and yield simulation models.

In many research fields of biology, the optical light microscope has been widely used to observe plant tissues and cells. The use of a TV camera and monitor instead of naked eye facilitates observation. The use of an image processor for analysing signals from the camera also made it possible to evaluate cell growth, the shape of organelles and their colour tones, etc. Optical image monitoring system was also used by Twidwell et al., (1989) to measure plant tissue defects. This method was destructive and it required approximately 15 minutes per sample. Use of remote sensing methods for macro and micro levels was also evaluated by Nilsson, (2009) for plant pathology. The study of Ling *et al.*, (1995) also showed good results on remote sensing techniques. The work by Tucker and Chakraborty, (1997) described an algorithm to detect and characterize disease lesions on plant leaves. The proposed system was able to detect the lesion type and the percentage of diseased leaf area. In another research, a novel method was used. To detect the surface defects of apple and it was concluded that the experimental hardware system was found practical, feasible, and effective (Li et al., 2002).

In the last years, novel non-destructive methods using tablets and smartphones have been developed to detect plant growth and health. For example, a novel android app for smartphones and tablets was developed to predict the corn leafs chlorophyll content (Vesali et al., 2015). In another research, an android device was used to predict the colour levels of the rice leaf. Their results showed that the system predicted the needed amount of nitrogen fertilizer (Intaravanne and Sumriddetchkajorn, 2015).

Plant Disease Detection

When plants and crops are affected by pests it affects the agricultural production of the country. Usually farmers or experts observe the plants with naked eye for detection and identification of disease. But this method can be time consuming and expensive. Automatic detection using image processing techniques provide fast and accurate results. This section discusses numerous techniques to identify plant diseases using image analysis. In the study of Rastogi et al., (2015) the disease present in the leaf was detected and classified based on the segmentation of defected area. They concluded that the developed method is an effective and efficient method. But the demerits are that it is not much adaptive and hence requires extensive training (Rastogi et al., 2015). In another research, colour transformation structures were obtained by converting images from RGB to HSI color space (Tripathi and Save, 2015). It was concluded in their research that it is a fully automatic, cheap, fast and reliable system. They also concluded that the disadvantages of the developed method are that neural networks cannot be retrained and hence requires a long training period (Tripathi and Save, 2015).

In another research, a colour based algorithm using specific threshold was developed to detect plant leaves diseases and it was reported that the proposed system can define and classify the examined diseases with 94% accuracy (Arivazhagan et al., 2013). Sanjay and Nitin, (2013) developed a colour based monitoring system to detect diseases on the plant leaf. In addition to this, a novel methodology was used to classify the diseased plant leaves and it was concluded that the results showed the effectiveness of the proposed scheme (Muthukannan et al., 2015).

Islam et al., (2012) aimed to build automated disease identification approach for plant leaf with computer vision based recognition system by evaluating the performance of Genetic Algorithm (GA) and Probabilistic Neural Network (PNN). They concluded that the developed algorithm has more precise classification rate like 97% than Neural Network classification rate like 94.75% Kanjalkar and Lokhande, (2013) developed an algorithm to detect four different diseases by using image processing and computing different features like size, colour, proximity and average centroid distance. They concluded that the results of the experiments confirm the robustness of the proposed system (Kanjalkar and Lokhande, 2013).
In another research, watermelon leaf diseases were evaluated by neural network analysis based on the image data. They concluded that the type of leaf diseases achieved 75.9% of accuracy (Kutty et al., 2013).

Al-Hiery et al., (2011) used an image analysis system to detect grape diseases. It was concluded in their research that the best results were obtained when FFBP Neural Network was learned to identify (Al-Hiery et al., 2011). In another research, leaf diseases were identified by the machine learning approach. They concluded that image processing of crop colour was important and cost effective method (Mainkar et al., 2015).

Pest Detection and Identification

The pest detection and classification in the plants is crucial to be sure good production (Parida et al., 2015). This is very important because it can help to fight with the pests. It can also reduce the use of pesticides (Parida et al., 2015). Together with the image processing, there are different kind of techniques to detect bio-agressors. Image monitoring involves recording a static or dynamic image and using different pre-processing techniques to the image (Parida et al., 2015). For example, Yang et al., (2011) used image processing method to count pests numbers. In their research, motion estimation, multiple-frame verification etc. were used (Yang et al., 2011). In another research, monitoring systems were used to record images of infested crops by coffee berry or aphids (Murali et al., 2013). In addition to this study, images of the damaged leafs were automatically recorded to detect the bio-aggressors using the image processing techniques (Ganesh et al., 2013). In another research, Martin et al., (2008) reported that the image recording process with insect activity. There are different kind of methods to define pests' type such as whiteflies, aphids, and borers. For example, aphids and whiteflies were defined by Rupesh et al., (2013) using a camera with zoom function. In their research, some features such as eccentricity, colour and mean, were used in SVM to detect and identify aphids or whiteflies (Rupesh et al., 2013).

In another research image processing method was performed by Prathibha et al., (2014) to define borers on tomato plants. They used the segmentation method to detect the target area. Cho et al., (2007) developed and used an algorithm with size, boundary shape and colour features to detect adult pests like whiteflies, aphids and thrips. Miranda et al., (2014) used a wireless camera and image analysis method to detect some pests. In another research, image processing method was used by ThulasiPriya et al., (2013) to count the insect. They used edge detection, RGB and convolution methods in Matlab software. Kandalkar et al., (2014) developed and used image segmentation to select locations and find some characteristics of the target object. In another research, a new method based on image analysis was performed by Barbedo, (2014) to quantify whiteflies on soybean leaves. His approach allows counting to be fully automated, considerably speeding up the process in comparison with the manual approach. The proposed algorithm is capable of detecting and quantifying not only adult whiteflies, but also specimens in the nymph stage. They concluded that this proposal was entirely developed using soybean leaves. Thus it can be used also for other kind of plants with little or no changes in the algorithm. The system employs only widely used image processing operations, so it can be easily implemented in any image processing software package (Barbedo, 2014). In the another research, the implementation of different image processing techniques was evaluated by Miranda et al., (2014) to define insect pests by the developed monitoring system to predict pest densities. Their results showed that the proposed system has a potential to detect pests in the rice fields (Miranda et al., 2014). Maharlooei et al., (2017) developed an image processing technique to define and count different sized soybean aphids on a soybean leaf. They concluded that the results also showed that the developed system with an inexpensive camera gave satisfactory results under high illumination conditions (Maharlooei et al., 2017). In the another research, the implementation of different image processing techniques was developed by Gopal, (2016) to define pests by developed monitoring system in order to minimize subjectivity and labour. In another study, an image monitoring system was successfully used to define oriental fruit moths (Zhao et al., 2016).

Monitoring methods for plant growth and health

IR Thermography

The temperature of canopy is the major indicator for plant response against environmental influences like solar radiation, water availability and air temperature (Kacira and Ling, 2001). However, the leaf temperatures of plants have also been related to plant transpiration, potential of the leaf water and soil water deficit (Kacira and Ling 2001). It is very useful to know various leaf temperature regions because they can be used as a sign of transpiration (Hashimoto et al., 1984). Water stress was also predicted from destructive leaf measurements. Hashimoto et al., (1984) developed a thermal image analysis method on water stress in sunflower leaves.

Aerial Infrared Photography

Aerial infrared (IR) photography was often tested in the detection of infectious and non-infectious crop diseases almost all of the countries in world. Infrared colour photography and spectral reflectance was used by Blazquez and Edwards, (1983) to detect some diseases like Phytophthora *infestans* and *Alteria* solani in tomato and potato plants and *Cladosporium fulvum* in tomato plants. Blazquez, (1989) performed a similar research to detect the diseased citrus grove by CIR photographs. In related studies, Blazquez and Edwards, (1983) conducted plant disease observations using aerial colour photography with colour infrared and black-and-white infrared films of potato and tomato fields. Late Blight and Early Blight diseases in tomatoes and potatoes were determined by the visual observations of the transparencies (Blazquez and Edwards, 1985).

Plant and Plant Part Identification

As one of the most useful methods of plant recognition, computerized image recognition has focused on plant morphology, (Batchelor and Searcy, 1989). If the edge and border patterns of the leaf or overall shape of the plant can be determined, it can be a reliable sign of plant type. Grayscale and colour image processing systems were tested by Meyer et al., (1988) to determine the percent residue cover on soil surface. Image analysis software was developed by Humphries and Simonton, (1993) to recognise geranium cutting features such as main stem, petioles and leaf blades. A systematic method to record images of plants was studied by Wang et al., (2001). Some parameters were evaluated to simplify investigation of genetic behaviour by image analysis technology. The results of algorithms were compared with the synthetic images of the real plants and the correlation coefficient between the leaf and its synthetic image was found as 0.88 by Wang et al., (2001). Portable equipment, suitable for field instrumentation, has been developed recently and is powerful enough for investigation and diagnosis of internal rot in living trees (Onoe et al., 1983).

Nuclear Magnetic Resonance (MR) instrumentation methods are also widely used in the fields of biological and medical research as an analytical means for obtaining information about the chemical composition and reaction process in organisms. As an example of MR imaging of plants, distribution of root systems and soil moisture were measured (Bottomley et al., 1986). The results suggested that the MR imaging was an effective method for measuring spatial distributions of water in soil and roots. By analysing the image, information about the growth in seedling and root, may be provided without destroying the plant itself and the soil environment.

Plant Discrimination

Development of an image processing system is a prominent and essential step to discriminate crop seedlings from weeds. It is also very important to develop automatic and non-chemical weed control methods in agriculture (Aitkenhead et al., 2003). Horgan et al., (2001) reported that the results of their project showed that the objective image processing was useful in the distinction of carrot cultivars. The different transmutations of the red, green and blue colour space were evaluated by Philipp and Rath, (2002) to find the most efficient method to separate plants recorded by a video camera. To identify carrot seedlings from ryegrass and fat hen weed, two methods were applied by Aitkenhead et al., (2003) using digital imaging.

Robotic harvesting

The image analysis methods give the potential to perform selective harvesting, and these methods can be used to replace manual harvesting of fruit. In literature, some studies have been reported (Whittaker et al., 1987; Slaughter and Harrel*,* 1987) to identify agricultural products by using the application of computer vision. Image processing was also tested to recognise green tomatoes in plants (Whittaker et al., 1987). In another research, software was developed by Sites and Delwiche, (1988) for robotic harvesting of fruits. The objects in the images were detected with 92% accuracy and the fruits were recognised with 89% accuracy. In a recent study, an algorithm was developed by Payne et al., (2014) to predict mango yield on the tree. They concluded that the detection approach with this algorithm can be used as a tool to detect mango.

Yield estimation and maturity assessment of the fruits

Yield estimation in an orchard helps growers foresee yield visually and therefore prepare them to take effective decisions. An apple yield mapping system was developed for real-time assessment of apple quantity indicated by apple reflectance using a multispectral image sensor (Kim and Reid, 2004). Estimated yield data was compared with reference data recorded by counting apples manually. Overall correlations were obtained between multispectral image sensor estimation and the reference measurement along the 148 trees resulted in R^2= 0.79 (Kim and Reid, 2004). Apples were also sorted by Kavdir and Guyer, (2008) using different pattern recognition methods. They concluded that the best classification results were obtained with multilayer perceptron neural network method. In another work, Herold et al., (2005) defined a spectral optical monitoring method for fruit maturity development in an apple orchard, in order to find the optimum harvest date. They measured the spectral optical reflectance of the apple fruit in visible and near infrared wavelength range, non-destructively in the orchard. Since several components of fruit show specific light absorption in this wavelength range, this method could detect physiological changes according to fruit maturity process (Herold et al., 2005). Most important light absorbing component is chlorophyll that is responsible for the fruit green colour. With increasing fruit maturity, the chlorophyll content decreases. This decrease, in this research, was detected by using the so-called red-edge wavelength which is the inflection point at red light spectrum (Herold et al., 2005).

In another study, a colour image processing method was developed by Choi et al., (1995) to identify and classify fresh tomatoes according to their maturity. The results indicated that the tested tomatoes were classified with 77% accuracy. In addition to image analysis techniques, X-ray computational tomography, can also be used for obtaining information about the internal structure of a living organism. In another research, the prediction of mango crop yield by analysing images of the trees was studied by Payne et al., (2014). In a recent study, qualities of tomato with different maturity stages were investigated by Takahashi et al., (2013) using image analysis technology. They concluded that there was a little fruit colour change in tomato with storage in large maturity stage (red fruit) regardless of storage temperature.

Conclusion

The role of image monitoring systems to evaluate plant growth and health were reviewed in this manuscript. Various image analysis systems were used to assess the plant growth and health in literature with various degrees of success. Some feature variables like size, shape and colour were used to detect the object in the plant image and to assess the growth and health by image processing. Developing the image analysis algorithms can increase the accuracy and speed to fulfil the needs of systems. However, integrating image analysis algorithms into special hardware can fairly reduce the time consuming.

With developed fast algorithms and cheap hardware solutions, image processing methods will have an increasingly important role in growth and health of plants assessment in the future. This method ensures to use less pesticides, optimum water usage and fertilizers by detecting some problems and plant situations in time. This method can also help to protect the natural balance of the ecosystem.

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