

SZENT ISTVÁN UNIVERSITY

Plant diagnostic by leaf movement image
processing

Thesis of PhD work

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1. INTRODUCTION

This section shows the aim of the work. State of the plants should constantly be monitorized and controlled energy efficiently with low cost, and without harming the plants.

1.1. Importance of the topic

Due in part to rapid population growth and urbanization in developing countries, water use for households, industry, and agriculture will increase by at least 50 percent by 2025. 70-80 percent of the world's water use is used in the irrigation sector. Increased competition for water will severely limit the availability of water for irrigation, which in turn will seriously price water to reflect its cost and value. Utilizing the fact, that the prices of computers and PC connected devices are dropping fast, the following goals were set to measure plant leaf movements.

1.2. Goals

The aim of the work is monitoring plants canopy in greenhouse: tomato, cucumber, paprika from the side, measuring leaf movement with simple devices, in the visible light spectrum, using low cost automation.

Low cost greenhouse measurements:

1. Low resolution camera in a model greenhouse with artificial light and background, for lateral monitoring of leaf and stem movement of tomato, paprika and cucumber. One plant or group of plants with leaves covering each other.
2. Be able to work for greenhouse measurement in natural light with no direct sunlight, without special lighting. Wind and other effects are not to be counted.
3. Be able to recognize the visual changes as the plant growth
4. Follow circular movement of plants.
5. The counting requirement of the camera should be as low as possible to help the measurement in a real greenhouse environment: changing temperature, humidity, wireless communication, using solar energy or accumulator. The energy requirement of a low energy consummated industrial computer with small processing ability, without moving parts and an industrial camera and a signal sending monitoring unit depends on the size of the images and the algorithm.
6. User friendly and adjustable environment, be able to store, analyze and compare the measured data.

Develop algorithm:

1. Develop and analyze algorithm to automatic recognition of stem and leaf on horticultural plants: cucumber, paprika, tomato.
2. Develop and analyze to measure leaf and stem inclination on horticultural plants: cucumber, paprika, tomato. Leaves hiding behind each other should not disturb the measurement.
3. The method should be applicable to measure one plant, group of plants, and parts of plant. The size of the area of interest should be variable, the leaves and stems sometimes visible sometimes covered should not disturb the measurement.
4. Measurements following each other should not be sensitive for plant parts moving in or out from the area of interest.
5. If some parts in the area of interest have no valid result, the results from other parts of the interest should be used itself.
6. The algorithm should work as simple as possible, without special lighting, optical or software filter or picture correcting. In order to store and analyze, images, should be as small as possible.

Inclination – water content, well being estimation:

1. Plant leaf and stem inclination estimation in degrees. Leaf inclination, stem inclination, leaf and stem inclination compared to plant water content.
2. Plant well being (wellness) measured for plant water state
3. Estimate drought stress.

Inclination – irrigation control:

1. Design and build an automatic irrigation system, controlled by image processing only.

2. MATERIAL AND METHOD

The experiments were carried out in a model greenhouse at the faculty of Physics and Process Control at the SZIE University in Gödöllő. Plants were monitored by a web camera. The camera took images at a given time scale about the plants. Images were processed and stored by a self developed algorithm. Results were presented by an other self developed software. The camera was set at the opening side of the greenhouse, 45 - 55 cm apart from the measured plants. White background was set at the other side of the model greenhouse.

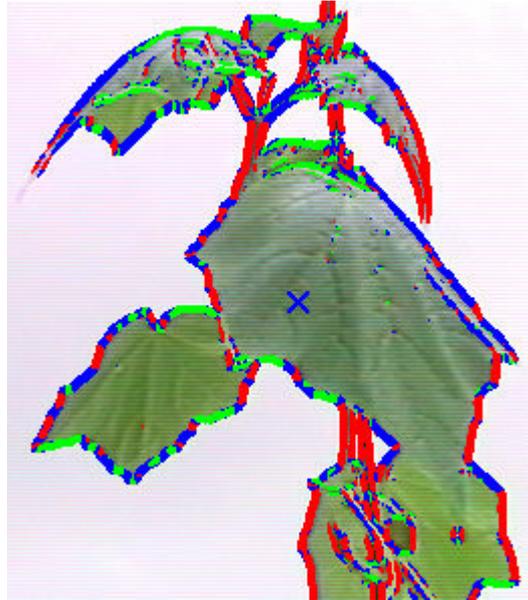
The method used

The measurement of leaf and stem direction was based on lateral images. The measured direction does not give the real three dimensional direction, it is calculated in the plan perpendicular to the axis of the camera, and counted from the horizontal direction. Since real leaf direction is very difficult to measure, the directions around the leaf and stem edge points were calculated.

The algorithm looks for edge or border pixels on the canopy image, for example where leaf blade and the background has a border line. The dark pixels on the edge of the blade next to the white background can make a strong edge between the plant and the white areas. The directions around the edge points are measured. If leaves are partly covering each other, and the contrast between the leaf blade and the leaf behind is strong enough, the direction around the edge points can be measured.

Direction histogram

The measured directions are rounded to integers between 0° - 90° according to the angle measured with the horizontal direction. The histogram shows the amount of edge points with same direction. An other histogram can be created for specified direction groups. On fig. 1 a cucumber in a model greenhouse is measured. The directions are grouped into three groups. Each group is marked with the same color. In the first group, marked with green color are the edge points, where the direction of the plant is close to horizontal. In the second group, marked with blue color, the edge points have a direction between 30 and 60 degrees compared to horizontal direction. The red color is used for the group of edge points, where the direction is close to vertical. The more points are green, the more turgid is the plant.



- Green: 0°-30° Blue: 30°- 60° Red: 60°- 90°

Fig. 1. Leaf and stem inclination on cucumber, compared to horizontal direction, in degrees

Leaf and stem direction measurement

The algorithm looks for local edge directions on the canopy image and calculates their angle compared to the horizon. Directions are counted between 0° and -90° as the difference from the horizontal direction. Generally the bigger is the wilting rate the farther is the leaf blade direction from 0° (horizontal direction) and the closer is the leaf blade to -90° (vertical) direction. A turgid leaf with an upward (positive) direction would suggest the algorithm that the leaf is wilting, because it automatically converts the positive angles to negative. As a result the developed algorithm works well for plants either having a turgid state with a leaf inclination lower than the horizontal direction, or for plants in water stress condition, when leaves go under the horizontal direction.

The developed algorithm

Because of the requirements in chapter 1 the algorithm works with black and white images suitable for fast processing and low storage place.

Edge detection is carried out with a variable sized prewitt operator that analyses a small part of the image. A matrix is running over the image and looks for edge points with strong contrast. Prewitt operator was chosen because it can detect edge points, calculate direction and the strength of the contrast in one step. It works well on an unfiltered image. When the matrix finds an edge point with strong contrast, its position is stored, and the direction is calculated.

In the next step leaf and stem points are separated.

Direction histogram is calculated from the amount of edge points between 0 and -90° degrees. The histogram shows leaf and stem inclination and the state of the plant.

Model for leaf and stem separation

The program thresholds the image by the average greylevel value of the edge points and the lighter ones will consider as the background pixels. All the others, the darker pixels will be plant points, either leaf or stem ones. If any of the darker pixels is not recognized as a stem point, it is counted as a leaf point. It is assumed that the plant consists only from leaf and stem.

The program runs the matrix over each point on the image and checks for stem pixels. To consider a pixel being a stem point, the pixel and the surrounding matrix has to fulfill 5 criteria. If any of these criteria is not coming true, the pixel is not marked as a stem point and the algorithm checks the next pixel on the image.

a/ Criterion

User can set the minimum amount of edge pixels in the matrix, to qualify a point as a stem pixel. If there are more stem points in the matrix, the criterion is not passed.

b/ Criterion

The program calculates the difference between each direction and the average direction. Summarizing the differences and dividing by the number of edge points in the matrix, will give the average direction difference. If it is smaller than the user defined value, then it is counted as 0. In the next step the program calculates how many percent is the average direction difference of the average direction. If it is smaller than the user defined value, the second criterion is completed.

c/ Criterion

The outside of the matrix should be lighter than the inside. The program verifies all the edge points in the matrix on the right side, and the left half edge points as well if their left side neighbor pixels are lighter than that on the right side. If it's true for a pixel, a counter value is increased by 1. If not, the counter value is decreased by 1. After checking all the edge points in the matrix, the counter should have a positive value.

d/ Criterion

This criterion ensures that the center pixel of the matrix is to be darker than its average. The given point must have a darker greylevel value than the average greylevel value of the surrounding matrix.

e/ Criterion

The last criterion calculates the number of edge points, whose right side neighbor pixels are lighter than that on the left side. It also calculates the number of edge points whose left side neighbor pixels are lighter than that on the right side. The ratio between the difference of these values and the number of edge points must be smaller than a user defined value. The number of edge points, whose bottom side neighbor pixels are lighter than that on the upper side are counted. The number of edge points, whose upper side neighbor pixels are lighter than that on the bottom side are also counted, and the difference between them is calculated. The ratio between the difference, and the number of edge points must be smaller than a user defined value. When this user defined value is bigger than any of the two ratios, the 5th criterion is passed.



Fig. 2. Leaf [red] and stem [green] separation. Leaf edge points are brown, stem edge points are blue

2.1. Tomato leaf inclination and water content

In the experiment 10 tomatoes were grown in pots in a model greenhouse, under 14 hours light. Irrigation happened in the same time with the same amount of water for

all plants. Plant weight and height (60 cm) was about the same. Seven leaves were cut at every measurement, their fresh weight was measured and then dried in a drying chamber. Dry leaves were measured again. The average water content of the seven leaves was compared with the inclination measured by the camera.

2.2. Circular movement of the leaves

Measuring the circular movement, plant moving can be quantified. In the experiment cucumber movement was monitored after irrigation, and the cyclic movement of the regenerated plant for 5 days, to compare and make a different between the two movements. Leaf movement was estimated by up and down movements and by the rotational speed of leaf inclination changes.

2.3. Interactive irrigation

An USRobotics 640x480 resolution 24 bit color camera was set 50 cm apart to three paprika plants. In another experiment plants were changed to tomato. Fig. 3 and 4 show the group of plants in well being state and in water stress. On the images 15 pixels corresponds to 1 cm.

Irrigation was controlled by the visual appearance of the plants. White sheets were used for background.



Fig. 3. Tolerable inclination



Fig. 4. Not tolerable inclination

Images are processed and the leaf and stem inclination values were calculated. When the calculated inclination was more than the plant specific tolerable inclination, the control unit turned the irrigation on. Water pipe was set above the pots. (Figs. 3-5)

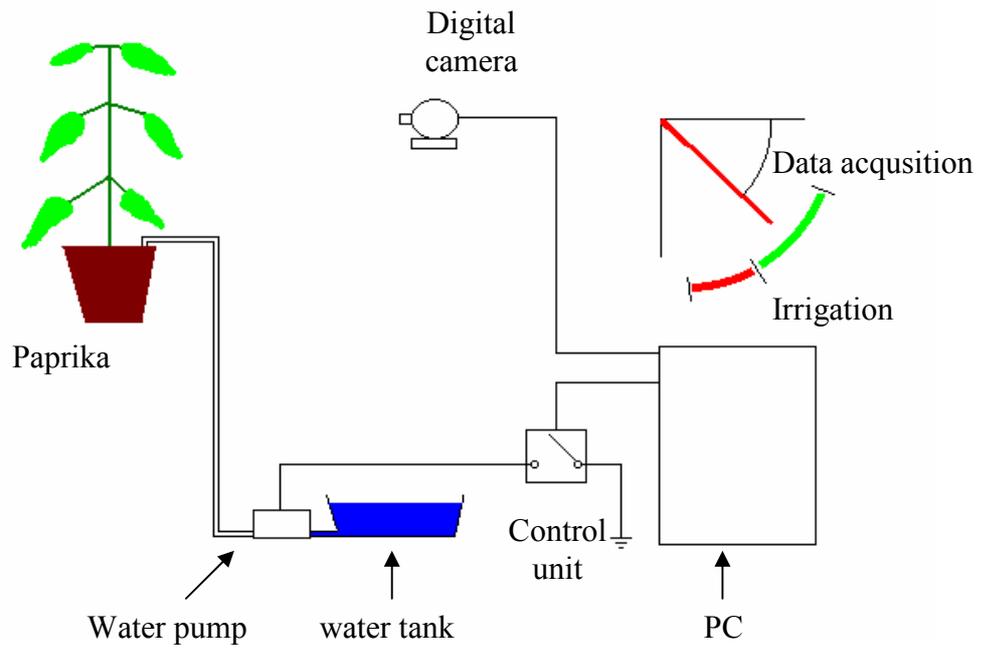


Fig. 5. Automatic irrigation

3. RESULTS

This chapter describes the results of the experiments about the image processing based inclination estimation, leaf water measurement, and automatic irrigation.

3.1. Tomato canopy inclination and water content

Experiments were carried out in a model greenhouse. Seven control plants were measured for leaf water content. Counting from the bottom, leaf water content from the leaves from the 5th. and 6th. stem were cut and measured in a drying chamber.

The average water content of the leaves of the seven control plants measured in the same time, can be seen on fig. 6.

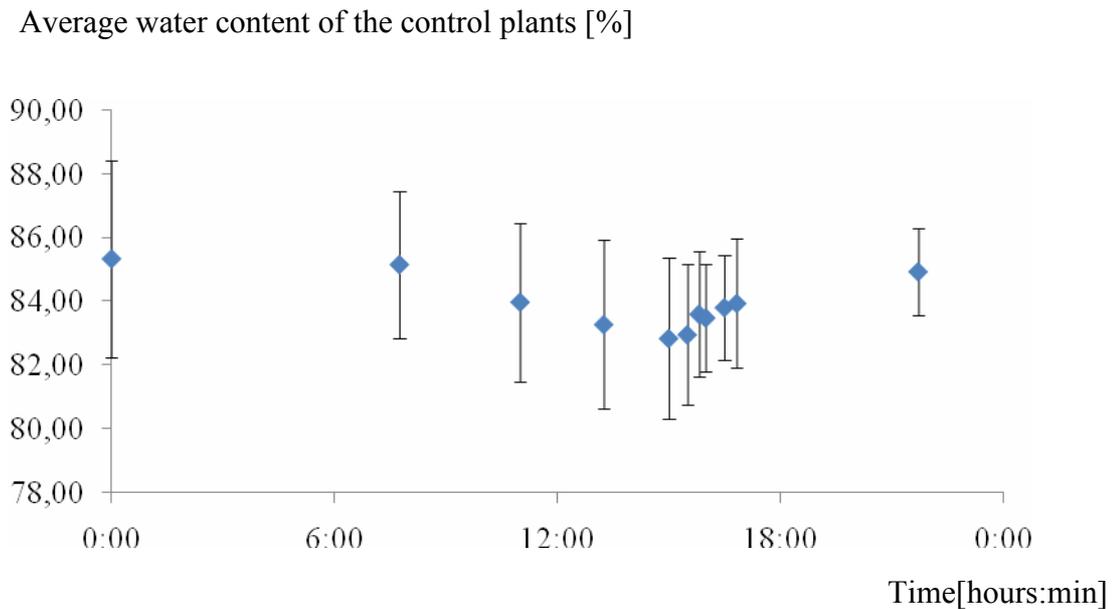


Fig. 6. Water content in the function of time [hour:min], with a 95% confidence interval

On fig. 7 the leaf, leaf and stem inclination are shown in the function of time. The different between the minimum and maximum values are marked with black arrows.

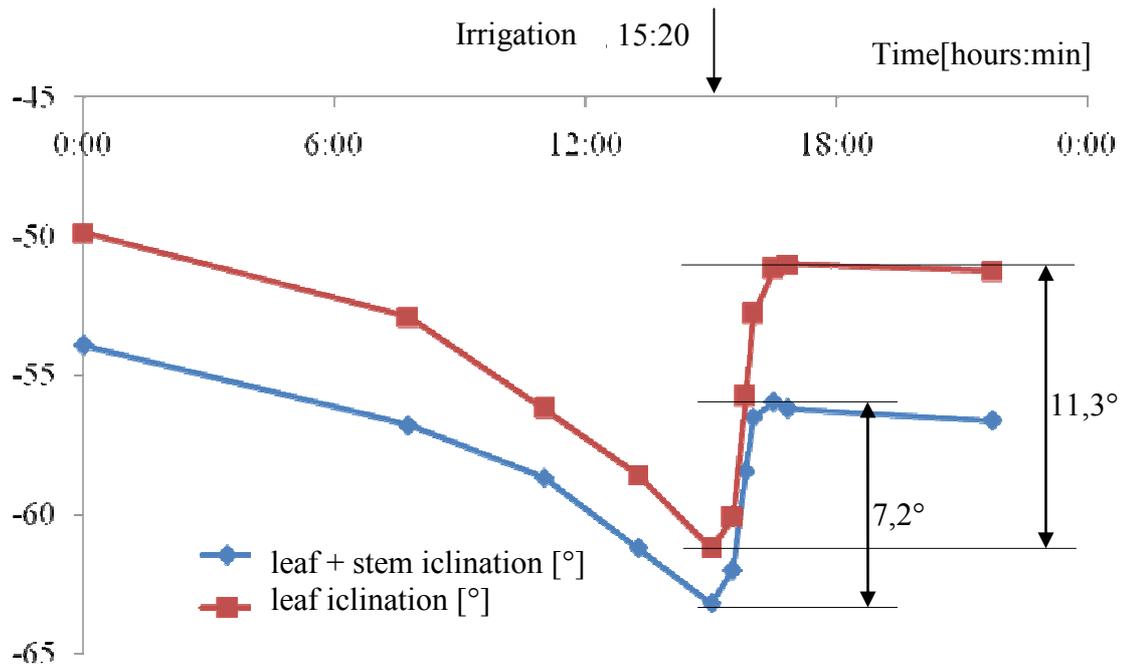


Fig. 7. Tomato leaf inclination, leaf and stem inclination at the time of fresh leaf weight estimation

From the results it can be seen that the average of leaf water content (fig. 6), has changed similarly to the inclination measured by image processing (fig. 7). Fig. 8 shows the irrigation schedule.

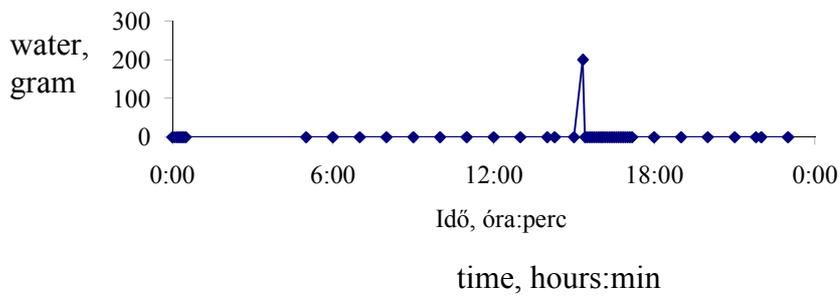


Fig. 8. Irrigation schedule during the experiment

The experiment shows that leaf inclination changes similar to leaf and stem inclination changes. The main stem does not move along with the leaves and stems, but recognized as a stem.

In the experiment the measured water content was calculated as the average of the water content of the seven leaves, measured in the same time.

The experiment can be separated to the period before and after irrigation, when plants water content decreasing and increasing. For irrigation scheduling the water decreasing period is more important, so the experiment focused on the period before irrigation.

3.1.1. Tomato leaf inclination and water content

For the leaf inclination based water content measurement I have worked out a validation method for tomato plants. From the leaf inclination I have calculated the leaf water content before and after irrigation. With an inclination-water content function I have translated the inclination values to leaf water content, and calculated the correlation between the measured and the calculated water content. The function is valid for the group of the measured plants. Leaf inclination water content function for other group of plants can be estimated with the same method. In the following, the application of the method in the experiment is described.

On fig. 9 the results of the 11 measurements can be seen. At each measurement the leaf inclination was estimated by image processing.

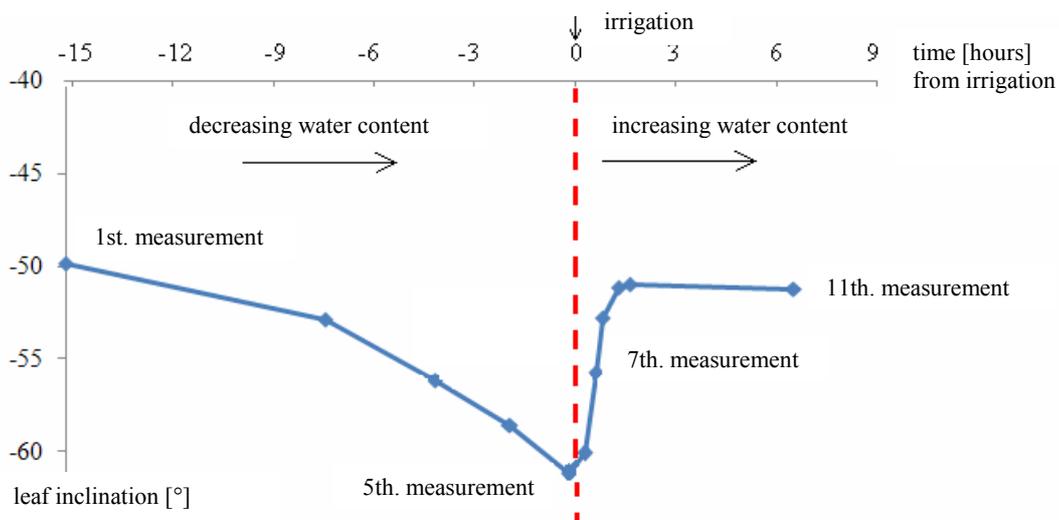


Fig. 9. Leaf inclination in the function of time

The images were analyzed with the algorithm developed for group of plants. A water content leaf inclination graph can be seen on fig. 10 each point represents a leaf inclination value and a water content value, calculated as an average of seven

leaves, with a 95% confident interval. Curve fitting to the points before and after irrigation was carried out by Microsoft Excel. The function of the fitted curve and the variance of the correlation coefficient can be seen on fig. 10, where:

$$R = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

x leaf inclination,

y water content,

R correlation coefficient between leaf inclination and water content.

For half an hour after irrigation, leaf inclination and water content changed in the same way. Later on leaf inclination recovered faster than leaf water content. During the last two measurements leaf inclination has changed a little, while leaf water content had been changing more. Results before irrigation shows fig. 10.

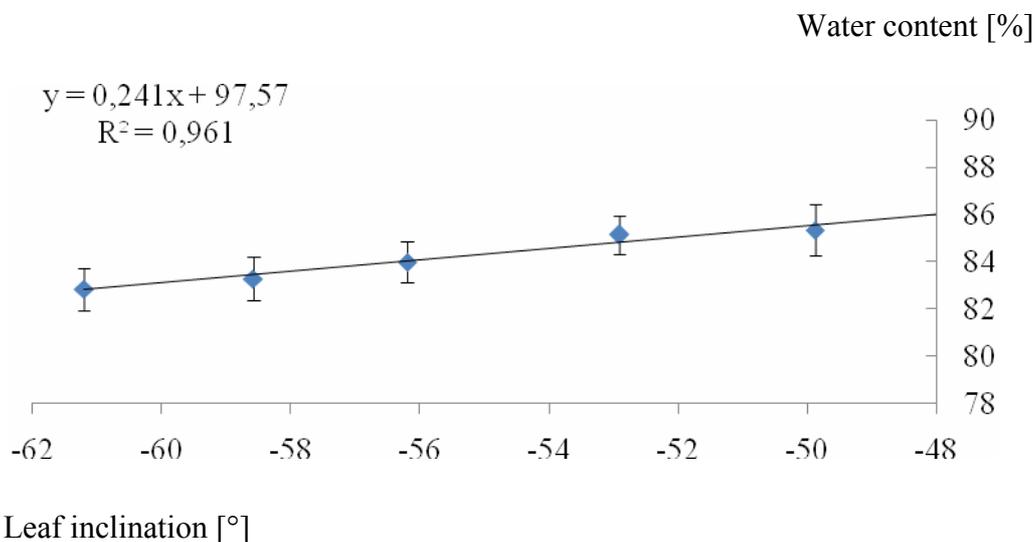


Fig. 10. Leaf inclination – water content before irrigation

From the beginning of the experiment until irrigation five measurements were carried out. In this time leaves were moving down, there were visible signs of wilting. After irrigation, during 6-8. measurements leaves were moving up, plants had been looking more vigorous. During the measurements 9-11. leaf inclination reached a peak. At the last two measurements leaf inclination changed a little, but leaf water content grown significantly.

At each measurement interval, the function of the fitted curve and the measured leaf water content fitting accuracy validates the measurement.

According to the experiment, during the time of increasing water deficit, the correlation is higher between leaf inclination and leaf water content then in the

whole measured interval or in the interval of increasing water content. Leaf water content calculated from the inclination of dryer leaves give more reliable results.

I have estimated the changes in leaf inclination and water content, between the maximum and minimum values.

The optimal leaf inclination state was at $-49,88^\circ$, the biggest inclination before irrigation was $-61,2^\circ$. The different between the minimum and maximum leaf inclination was 22,7%. The leaf water content changed from 85,33% to 82,85%, the different is 2,91%.

In the 15 hours period before irrigation a change of 2,91% in water content occurred. The function between leaf inclination and water content was:

$$y = 241x + 97,57,$$

$$R^2 = 0,961$$

Leaf inclination was measured on three plants, with partly hiding leaves.

3.1.2. Tomato leaf and stem inclination and leaf water content

The experiment happened similarly to the previously described (chapter 4.2) measurement, results apply for the whole image. On fig. 11 the measured leaf and stem inclination is shown in the function of leaf water content.

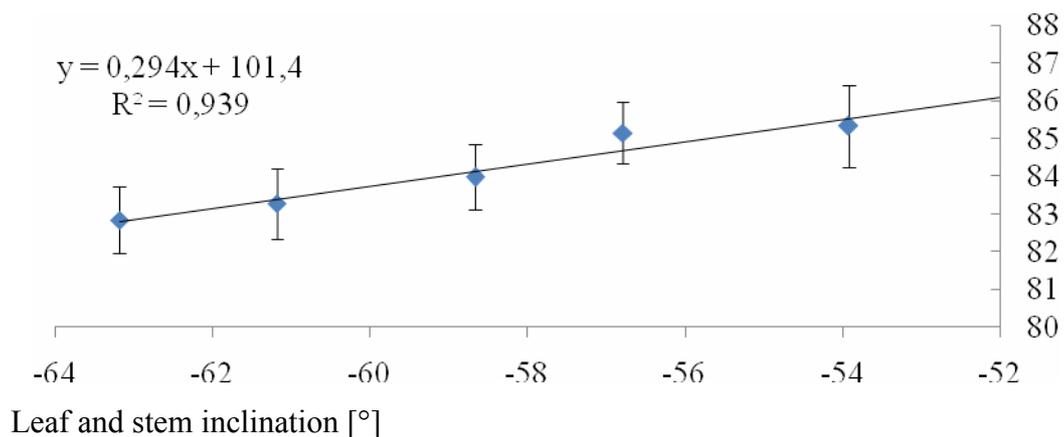


Fig. 11. Measured leaf water content in the function of leaf and stem inclination, before irrigation

During the last two measurements leaf and stem inclination changed a little, but leaf water content grown significantly.

According to the experiment, during the time of increasing water deficit, the correlation is higher between leaf and stem inclination and leaf water content then in the whole measured interval or in the interval of increasing water content. Leaf

water content calculated from the inclination of dryer leaves and stems, give more reliable results.

I have estimated the changes in leaf and stem inclination and water content, between the maximum and minimum values. Leaf and stem inclination was measured on three plants, with partly hiding leaves.

According to the measurements leaf and stem inclination during increasing water stress in 11 hours $4,75^\circ$ decreased, which is $0,43^\circ/\text{hours}$ rotational speed. Leaf water content changed $0,12\%/\text{hours}$.

Inclination decreased $4,52^\circ$ in the last four hours before irrigation, therefore the leaf and stem inclination rotational speed $1,13^\circ/\text{hours}$, and leaf water content decreased $0,28\%/\text{hours}$.

Summary of water content measurements

Based on the measurements in chapter 4.1, I have estimated the leaf inclination and the leaf and stem inclination of three tomato plants, with leaves partly hiding each other, and compared to the water content of control plants growing in similar environment. Using a self developed image processing algorithm, the measured inclination was calculated, and its function to the water content was estimated in different intervals.

The developed inclination-water content measurement is applicable to other group of plants, a general, objective and validable method for water content estimation in a given measurement range for a single plant or for group of plants.

I have estimated the canopy inclination for a group of plant. The change in inclination in a given time is a more general parameter, because leaf or stem inclination can be different at plants or at different parts of the plant.

The measurement of leaf and stem inclination is simple, and can be used at automated irrigation.

I have estimated the changes in leaf and stem inclination and water content, between the maximum and minimum values.

The optimal leaf and stem inclination state was at $-53,92^\circ$, the biggest inclination before irrigation was $-63,19^\circ$. The different between the minimum and maximum leaf inclination was $17,2\%$. The leaf water content changed from $85,33\%$ to $82,85\%$, the different is $2,91\%$.

In the 15 hours period before irrigation water content changed $2,91\%$. The function between leaf and stem inclination and water content was:

$$y = 294x + 101.4,$$

$$R^2=0,939.$$

Leaf and stem inclination was measured on three plants, with partly hiding leaves.

3.2. Measuring circular movement of cucumber

In the experiment images were taken of a freshly watered cucumber plant for five days, to analyze its circular movement. Images show the whole plant, 15 pixels on the image equals to 1 cm. The images and their histograms can be seen on figs. 12-14.

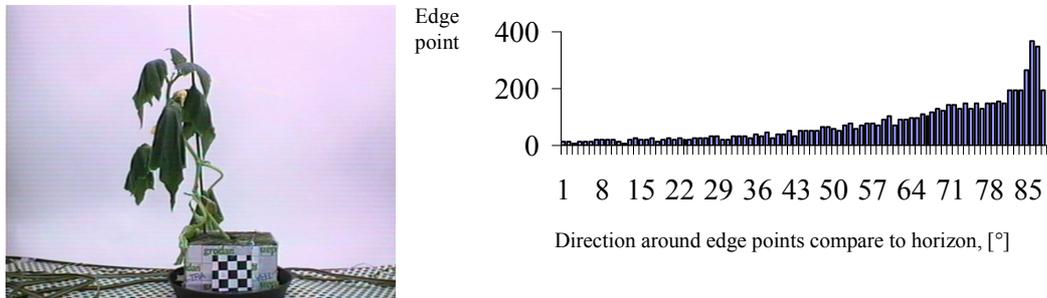


Fig. 12. Cucumber and its histogram, 15 minutes after irrigation

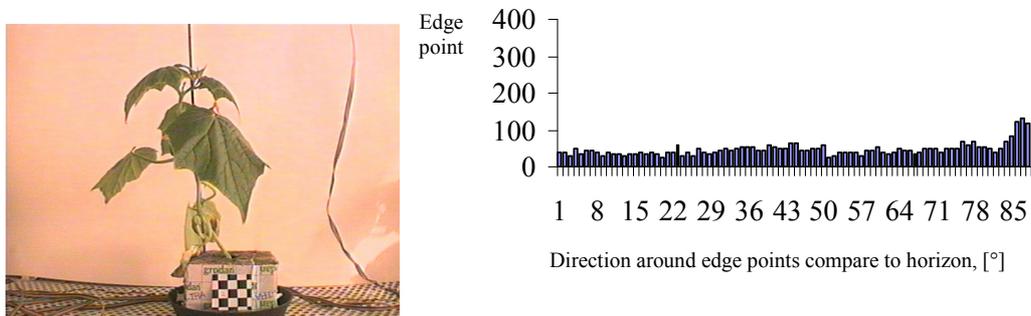


Fig. 13. Cucumber and its histogram, 34 hours after irrigation

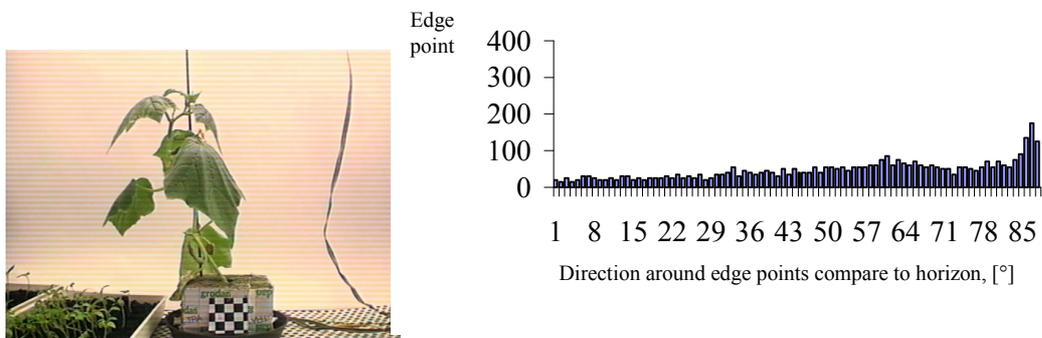


Fig. 14. Cucumber and its histogram, 48 hours after irrigation

On figs. 12 and 13 leaves were moving because of irrigation and circular movement. On the figs. 13 and 14 the circular movement daily 5° different and a starting water stress can be seen. On fig. 12 there is not much horizontal direction

on the histogram, but there are about 400 90° (upright) direction, partly because of the stick next to the plant. Fig. 13 shows a near horizontal canopy with about 50 horizontal (0°) directions, and a decreasing amount of 90° direction. Fig. 15 shows the average inclination at a given time.

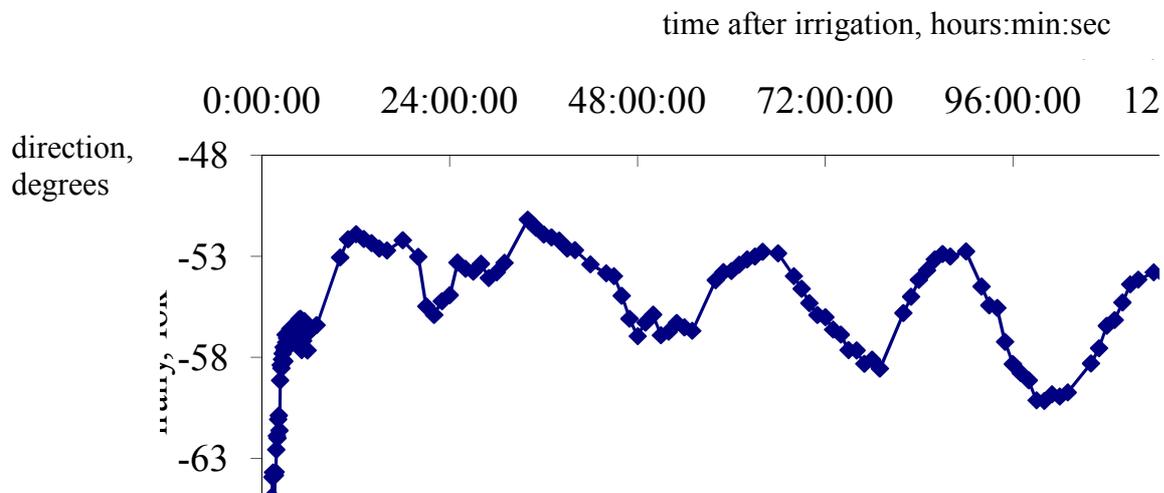


Fig. 15. Leaf and stem inclination during the experiment

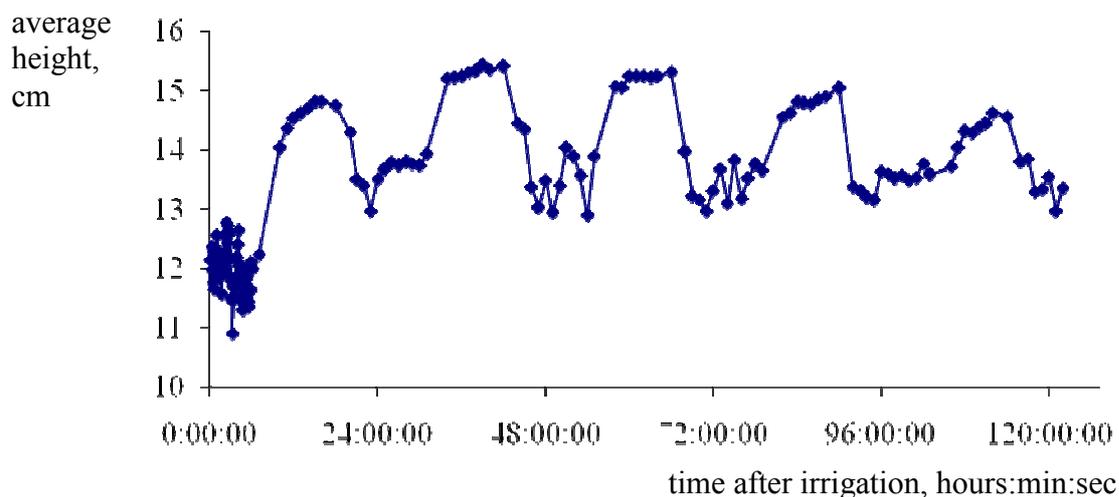


Fig. 16. Average height of edge points during the experiment

Circular movement was measured by the speed of the up and down movement of the plant, and leaf direction change in time, by the rotational speed.

During the experiment in the 22-121 hours after irrigation, from the daily leaf cycle maximum and minimum state and the time between, I have calculated the cucumber leaf rotational speed: 0,46 °/hour. Plant edge point's daily average up and down movement after irrigation between 16-121 hours can be measured from

the maximum and minimum positions. From one cycle movement and its time the cucumber leaf average speed: 1,78 mm/hour.

According to the measurements in the two and half hours after irrigation the rotational speed was eight time bigger than the average of the daily cycle 3,66°/hours around leaf and stem points. Edge points up movement were not significantly recognizable, partly because the leaves were turning around the main stem at the beginning, and the plant moved horizontally.

While the cucumber recovered in two and half hours after irrigation, leaf and stem inclination changed more than 10°. Cyclic movement resulted smaller movement, daily 5° up and down, and the leaf and stem edge points moved 1,5-2 mm/hour.

From the experiment it can be seen, that cucumber cyclic movement by the rotational speed (0,46°/hours) of the leaves and stem significantly different to the recovering movement rotational speed (3,66°/hour) after water stress. I have quantified the comfort state of cucumber by the leaf and stem rotational speed and average vertical speed in a daily cycle.

3.3. Automatic irrigation

This chapter deals with a leaf and stem inclination based irrigation method, using the algorithm developed to group of plants. The experimental plants were paprika and tomato.

3.3.1. *Automatic irrigation of tomato*

In chapter 3.2.1 it seemed that tomato leaf and stem inclination can be used for water stress measurements, and for automated irrigation.

A USRobotics 640x480 resolution 24 bit color camera monitored three tomatoes, half a meter away from the camera. Behind the 90cm tall plants white sheets were set for background. Images showed the upper part of the tomatoes, but the top of the plant was not seen on the images.

Decision making was based on the algorithm, developed to group of plants. Images were converted to grayscale, edge points were detected and the directions around edge points were calculated. Figs.17-20 show the number of edge points in the same direction on the images. Images were taken at different times. Histogram was calculated from 0° to 90°, one by one, but grouped into nine groups for the graphs. Fig. 17 shows the histogram before irrigation. There are twice as much edge points around vertical direction [-90 -80] than in horizontal [0 -10], because of the wilting leaves. On the next figures after irrigation leaves were regenerated, and leaf direction shifted to a more horizontal direction. Fig. 20 shows the histogram three hours after irrigation.

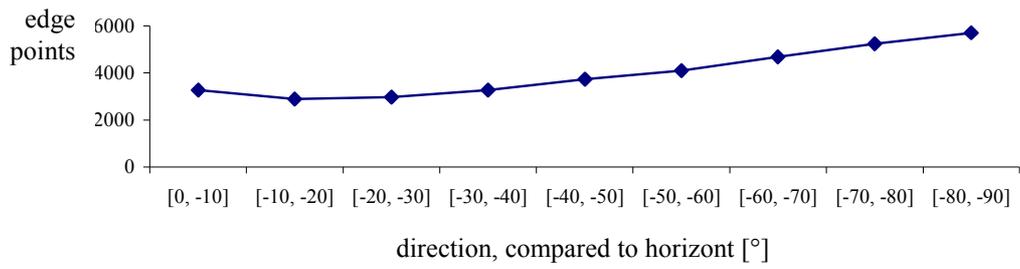


Fig. 17. Tomato direction histogram before irrigation

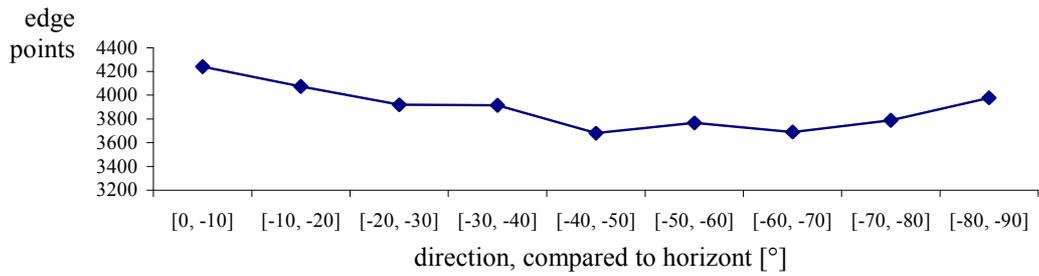


Fig. 18. Tomato direction histogram 45 minutes after irrigation

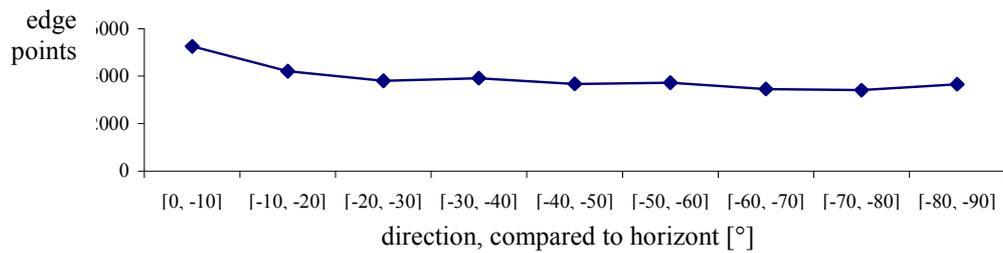


Fig. 19. Tomato direction histogram one hour after irrigation

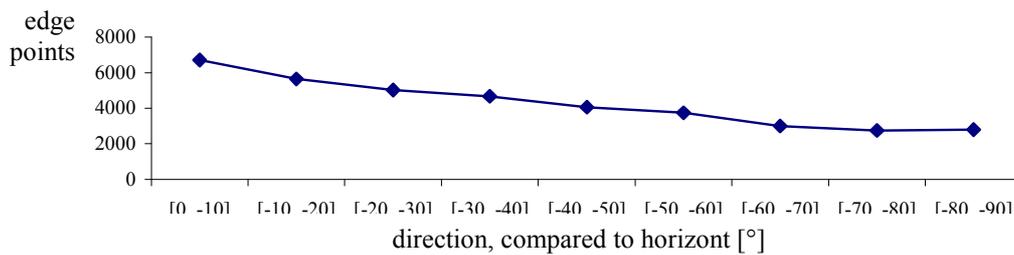


Fig. 20. Tomato direction histogram three hours after irrigation

When leaf and stem inclination is lower than a defined value, the irrigation controller turns on the water pump for a given time.

Automatic irrigation control:

In the chapter 3.2.1 a group of tomato plants were monitored, and inclination was estimated in well watered and in water stressed conditions. The different between the smallest inclination at irrigated state and the biggest inclination before irrigation was 17% (see at chapter 3.2). Water content changed 2.91%.

The goal of this experiment was the irrigation of similarly grown older tomatoes. Because the similarity between the groups, I assumed that the inclination water content curve is linear, and the changes in inclination and water content ratios are similar. Irrigation was set to keep the 17% inclination change from the previous experiment, so the different between the water contents supposed to be less than 3% between the well irrigated and the actual state.

According to previous measurements, the well irrigated tomato leaf and stem inclination was around -41° . Compare to that, 17 % inclination change was -48°

The goal was to keep leaf and stem inclination between -41° and -48° , by turning irrigation on when inclination had gone below -48° .

The control algorithm turned irrigation pump on and watered the tomatoes by 200 gram of water at each time, when leaf and stem inclination dropped below -48° , and plants were not irrigated in the previous hour.

The results of the automated irrigation for tomato plants can be seen on fig. 21 and fig. 22. From the results of the measurement it can be seen, that vertical movement of the plant can also used for irrigation timing. Irrigation scheduling was calculated only by the morphological appearance of the plant. Minimum time between irrigations was set to one hour, which was enough time for the tomatoes to recover to a more turgid state. The automated irrigation was tested on tomato and paprika, when leaves were partly hiding each other.

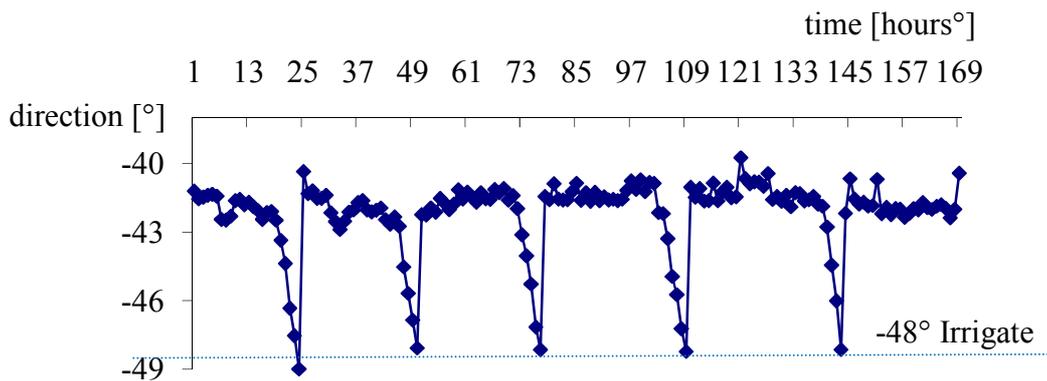


Fig. 21. Tomato leaf and stem inclination

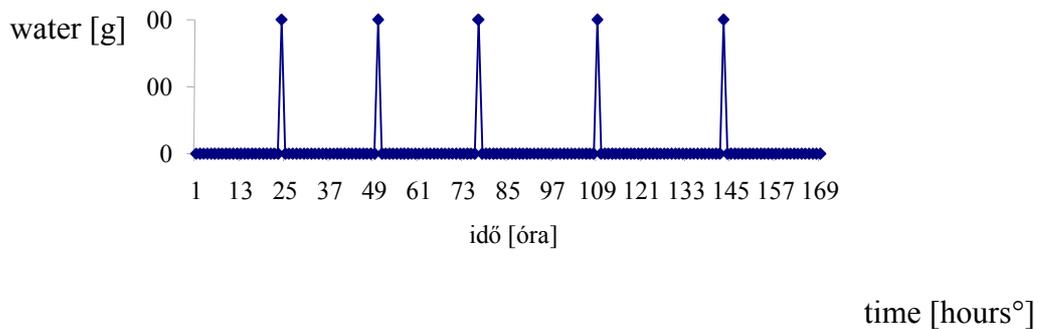


Fig. 22. Tomato irrigation during the experiment

3.3.2. Automatic irrigation of paprika

During the experiment irrigation scheduling was based on the images of paprika plants. There were three paprikas in a model greenhouse, 50 cm apart from the camera. Plants were 17 cm in height; the upper two third parts of the plants were image processed. Based on previous measurements, irrigation was set to turn on at 11% inclination change, that is the two third of the 17% inclination change used at tomato plants. It is also reasonable because paprika is more sensitive to water stress than tomato.

According to previous measurements, the well irrigated paprika leaf and stem inclination was around -46° . Compare to that, 11% inclination change would be -48°

The goal was to keep leaf and stem inclination between -46° and -51° , by turning irrigation on when inclination had gone below -51° .

The control algorithm turned irrigation pump on and watered the paprikas by 100 gram of water at each time, when leaf and stem inclination dropped below -51° , and plants were not irrigated in the previous hour.

The measured parameters can be seen on figs. 23-27.

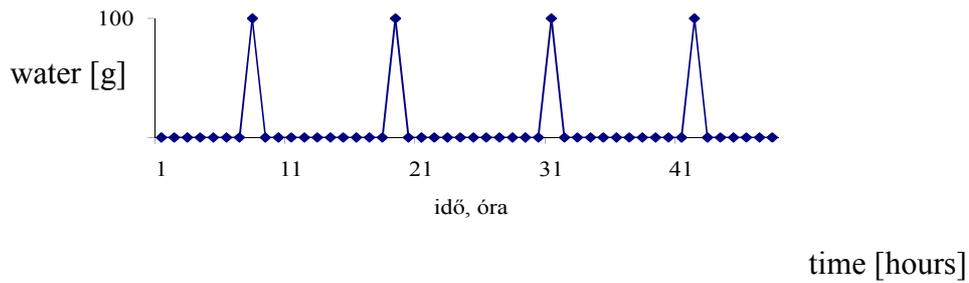


Fig. 23. Paprika automated irrigation

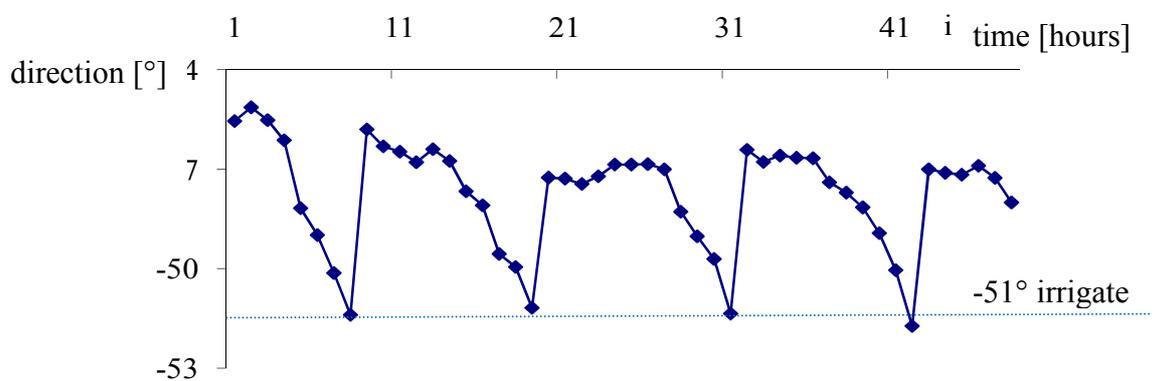


Fig. 24. Paprika leaf and stem inclination

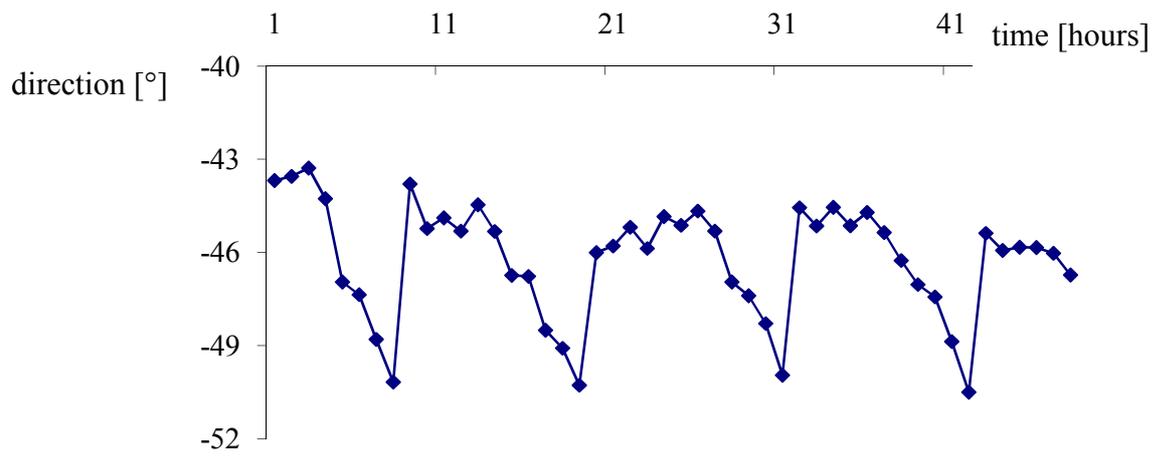


Fig. 25. Paprika leaf inclination

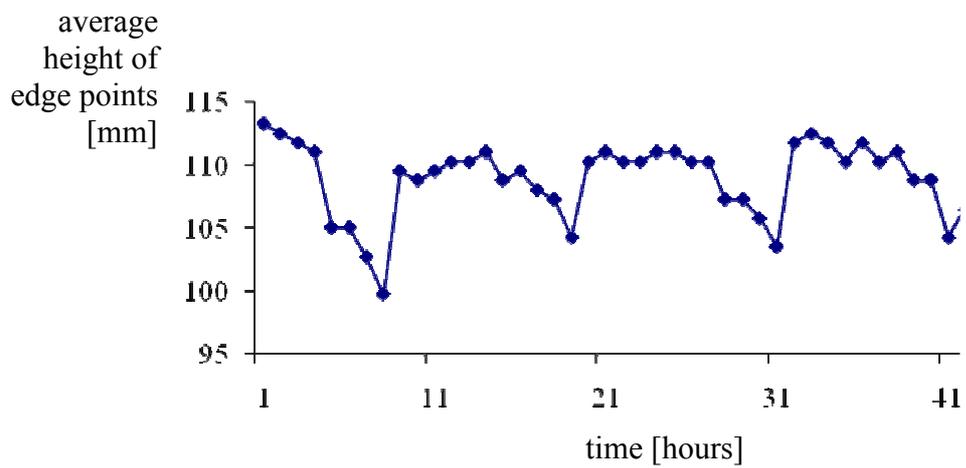


Fig. 26. Paprika edge points average height during the experiment

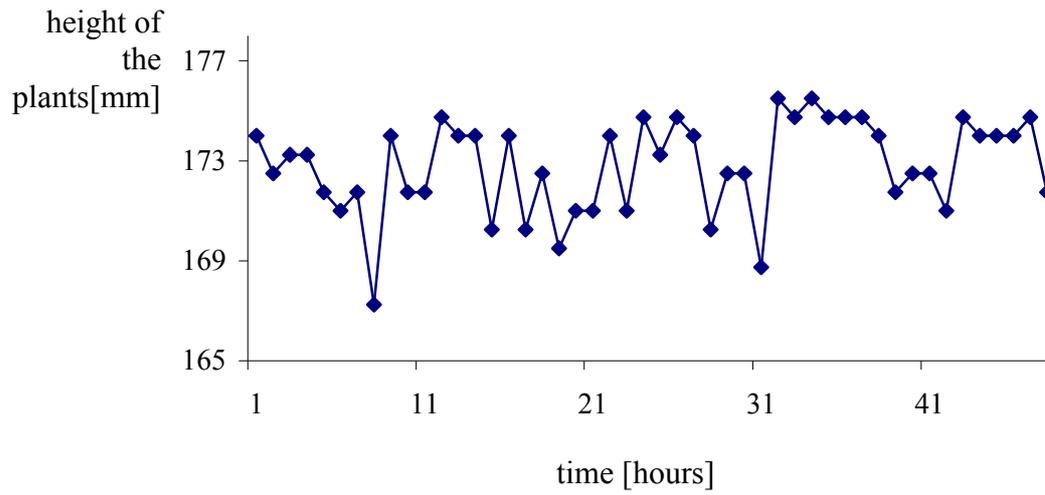


Fig. 27. Paprika height during the experiment

At -50° leaf and stem inclination paprika plants looked wilted, whereas at -45° they looked turgid. At tomato plants, wilted state appeared at -46° , turgid at -42° . Cucumber wilting occurred at -57° , turgid state had the visual sign at -52° .

4. NEW SCIENTIFIC RESULTS

1. Determination of plant leaf and stem inclination

Using a digital camera with artificial lighting and background, I have worked out a new method to analyze tomato, paprika and cucumber plants by image processing. The method can be used if the image contains leaf and stem only, and leaf and stem directions are pointing down. The method is applicable to one plant and to group of plants, without segmenting the covered leaves.

The basics of the method:

1. Edge detecting on the plants,
2. The average of the edge directions gives the inclination.
3. Histogram: edge directions rounded to integers between 0-90°. Different groups of direction intervals can be used according to the needs.
4. Direction intervals can be visualized by color scale. Edge points of the plant show the state of the plant, and the different among the canopy parts. Changes in scanning time can be seen as a movie.

The inclination histogram shows how even the canopy inclination is.

2. Leaf and stem separation

Using a digital camera, artificial light and background, I have developed an algorithm to separate leaf and stems with the help of previously defined morphological parameters of different types of plants (cucumber, paprika, tomato). A variable sized stem detecting matrix with uneven pixel lengths runs over the area of interest (ROI). The method checks the following parameters:

- number of plant points,
- different from the average direction inside the matrix,
- grayscale different between the inner and outer pixels of the matrix,
- average greyscale of the middle pixel of the matrix and the whole matrix,
- greyscale different among neighbor pixels.

The developed leaf and stem separation method is applicable to one plant and to group of plants, by setting the described parameters.

3. Estimation of tomato leaf inclination and water content relationship

I have worked out an inclination-water content evaluation method to objectively measure and validate the water stress of group of tomato plants.

I have estimated the water content and inclination changes during the experiment in the optimal state when leaf inclination was closest to horizontal direction, and in the worst state when leaf inclination was closest to vertical direction.

At the turgid state the smallest inclination was $-49,88^\circ$, and the biggest inclination before irrigation was $-61,2^\circ$. The change between the turgid and the wilted state was 22,7%. During that inclination change, water content dropped from 85,33% to 82,85%, so the different was 2,91%.

In the 15 hours period before irrigation, between the described states I have estimated the function between leaf inclination and water content of the group of plants:

$$y = mx + b,$$

where

x leaf inclination,

y water content,

$m = 241$, $b = 97.57$ parameters for the group of plants

$R^2=0,961$, R correlation coefficient between leaf inclination and water content

Inclination measurement was based on three plants combined analyzing, with partly hidden leaves.

4. Developing a method for cucumber comfort state (wellness) and circular movement estimation based on leaf and stem direction and vertical movement

From the maximum minimum positions of cucumber leaves, and for the measured time I have identified the average daily leaf and stem inclination rotational speed: $0,46^\circ/\text{hour}$, and vertical speed: $1,78 \text{ mm}/\text{hour}$.

With the measured leaf and stem rotational speed and the average vertical speed I have quantified the comfort of young cucumber plant at a temperature range of $27^\circ\text{C} - 33^\circ\text{C}$, and 39% – 48% relative water content, in a daily cycle.

I have identified the time for water uptake as 2,5 hours. From that time I have identified the leaf and stem inclination speed at water uptake period: $3,66^\circ/\text{hour}$. Based on the above calculated speeds, I have separated the cucumber canopy cyclic movement from the movement of regeneration of leaves and stems from water stress.

From the changes of leaf and stem rotational speed, and vertical movement I have identified the periodic time of cucumber circular movement in 24 hours.

5. Working out an image processing based irrigation control

I have developed an algorithm for irrigation scheduling. The fully automatic irrigation method constructed for tomato and paprika decides irrigation timing by image processing only, based on the average direction of the direction vectors in the environment of plants edge points. The critical values of average inclination can be estimated for an individual plant or for a group of plants, and for a given operational condition.

In case of tomato the leaf and stem inclination was between -41° and -48° compared to horizon, for paprika between -46° and -51° .

5. CONCLUSIONS AND SUGGESTIONS

Image processing is supported by the technical development. It can be used for monitoring plants and the environment of the plants. The extra information about the cultivated plant gained by image analyzing can help in yield optimizing, plant protection, and in avoiding water waste and environmental pollution. The regular, repeatable and destruction free information supports agricultural production and helps in water management. The low computing required image processing method for inclination can run on low cost computers.

The automatic plant monitoring matches the research fields of the Department of Physics and Process Control of the SZIE University. The faculty has various projects on automatic controlled greenhouse applications, using solar energy.

Validation can be approached at different ways, in this work inclination was compared to water content, and automatic irrigation was exclusively relied on inclination measurement:

- Based on the calculated leaf inclination of the plants and on the measured water content of monitored plants. Tomatoes age, size and their number in the group and the growing conditions were defined. From a series of similar measurements on inclination-water content, validation can be more reliable. The method can be used at water potential, and other plant water state based measurement.
- Irrigating paprika, tomato in defined condition for a defined time, controlled by inclination measurement only. Experiments with other kind of plants, and control plants for a longer time would show the different between inclination based and traditional irrigation control and the different between the yields.

A wilted or sick or stressed leaf probably moves different to a turgid or to a healthy one without stress. The developed method can be applicable to find stressed or sick leaves automatically. If wilting occurs before and after irrigation, it can be a sign of sickness or stress.

The described method can be attached to other image processing applications. It uses simple methods, ideal for low cost automation. The lighting, the camera and the computing speed can be developed with a low effort. The method has a broad space to develop by filtering images, and by using more robust edge detection algorithm.

6. SUMMARY

Horticultural and greenhouse plant production have to meet economical and environmental challenges. Detailed information about the cultivated plants can help in production and in irrigation. Plant monitoring and image processing tools were used to analyze plants movements.

For experimental plants I have used tomato, cucumber and paprika, the measurements have taken place at a model greenhouse and partly in a real greenhouse at Szentes, Árpád Agrár Rt. Images were collected by a 640x480 24 bit color camera, with artificial light and with background. The water content of leaves was measured in a drying chamber. The amount of images and image processing applications required automated image acquisition and processing. I have developed the algorithms in c++ and in a script program.

The plant analyzing algorithm for cucumber, tomato and paprika finds edge points on the image and separates them to leaf and stem. From the edge points there are several parameters were calculated, to describe the state of the plant.

According to the goals of this work, the developed method can be used for the following purposes:

- A direction histogram of the leaves and stems of the plant can be drawn as a graph, or it can be shown on the images on the edge points of the plants. The edge points of the plant can be marked with a color scale, according to the chosen direction intervals.
- Leaf water content can be estimated from the measured leaf inclination.
- Circular movement and water stress can be evaluated from the measured leaf and stem inclination.
- Leaf inclination can be measured automatically by separating the leaves from the stems.
- An automatic irrigation system was constructed, controlled by image processing only. Based on lateral images, leaf and stem inclination was calculated to control irrigation.

The hardware need of the method depends on the algorithms and the timescale of the measurement. The cameras similar to the one used in the experiments can be bought for 3-10000 forints. Because of the low computing needs of the algorithms, the method can be used on cost effective industrial computers.

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