Measuring Leaf Motion of Tomato by Machine Vision

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Keywords: stereo vision, image processing, transpiration, VPD, plant modelling

Abstract

For a better understanding of growth and development of tomato plants in three dimensional space, tomato plants were monitored using a computer vision system. It is commonly known that leaves of tomato plants do not have a fixed position and orientation during the day; they move in response to changing environmental conditions such as the position of the sun. For better understanding, it was desired to quantify this motion. Using a stereovision concept, two cameras were mounted in an experimental greenhouse a short distance apart from each other to enable depth measurement. Markers were placed on strategic spots on the tomato plant branches and leaves in the field of view of both cameras. Images were taken every ten minutes during daytime on several consecutive days. In the greenhouse, a virtual 3D coordinate system was defined and camera and tomato plant position and orientation were defined in this coordinate system. Image processing techniques were used to trace the markers and the 3D position coordinate of each marker in each image was calculated to obtain the course of a marker during several days. Stems, branches, and leaf nerves were considered as kinematic mechanical, robot like, links and corresponding theory was used to model and calculate the motion of stems and leaves of a tomato plant. Analysis of the images showed both small (1-2 degrees) and large rotations (10 degrees or more) of the branches and the different leaves on a branch during the course of a day. Leaves on one side of a branch showed a parallel motion in the same direction; the leaves on the opposite side of the branch showed a mirrored motion. However, deviating patterns occurred too. The developed method proved to be able to precisely quantify the motion of stems, branches and leaves of tomato plants during several days.

INTRODUCTION

Researchers of Wageningen UR Greenhouse horticulture observed from webcams in the top of a greenhouse that top leaves of tomato plants (*Solanum lycopersicum*) show remarkable motion during the day. They wanted to explain the observed motion of tomato plant leaves and test if relations between plant motion and environmental or plant physiological properties exist. Measurements of plant motion could also serve as support for Functional Structural Plant Models (FSPM). FSPM combine traditional plant modelling with a 3D structure to investigate the function of plant structure in plant development.

Directional growth or motion of plants (tropism) is a motion of a plant towards or away from a stimulus. This can serve several goals: optimization of photosynthesis, hiding from strong radiation, or preventing water stress. In earlier research, among others, Kacira et al. (2002) and Font et al. (2006) were able to determine water stress from changes in respectively top projected canopy area of flowering plant new guinea impatiens and side projected canopy images of cucumber plants. Pastenes et al. (2005) showed that bean leaves hide from strong sun radiation to regulate leaf temperature.

The water status of plants is strongly dependant on the transpiration rate. Transpiration is an important plant physiological process and directly related to sun radiation, humidity, wind speed, and temperature. Therefore one could assume that transpiration has an effect on leaf movement. Earlier applied plant measurement systems (Ivanov et al., 1994; Frasson and Krajewski, 2010) delivered an accurate static plant reconstruction, but were not able to measure at higher frequencies. Systems able to

Proc. IS on GreenSys2011
Eds.: C. Kittas et al.
Acta Hort. 952, ISHS 2012

measure at a higher frequency were not able to measure the plant structure accurately, e.g. earlier mentioned water stress determination methods. Biskup et al. (2007) measured diurnal changes in single leaf inclination of soy bean, but they did not consider the elevation angles between the leaves and the branches or the main stems. In literature several methods to measure optical plant properties are mentioned: single or stereo vision camera systems, 3D digitizers, Lidar systems and 3D cameras. Application of 3D digitizers would be laborious. Lidar systems work accurate but too slow for higher frequency measurements. Further, both systems are sensitive to wind. Based on searched literature, the accuracy of currently available ready-to-use 3D cameras at this scale was doubted. The desired situation is that a system will measure diurnal leaf and branch motion during several days with a frequency of at least two measurements per hour.

This paper focuses on developing a method to quantitatively describe motion of top branches and leaves of tomato plants during the day and on relating the measured motion to environmental or plant physiological properties.

MATERIALS AND METHODS

Plant motion measurements were done in the greenhouse of Wageningen UR Greenhouse Horticulture in Bleiswijk, the Netherlands, during September and part of October 2009. Two colour CCD cameras of the type Marlin F145C (Allied Vision Technologies) with a resolution of 1392*1040 pixels and with Pentax 4.2 mm wide angle lenses with a horizontal view angle of 86.77° were used. Images were taken every 10 minutes during day-time and stored at a standard pc situated in the greenhouse. Three series of measurements of three days each were made. Cameras were placed at a distance of $\approx$ 50 cm from the tracked branches and leaves, resulting in an image resolution <1 mm per pixel. The cameras were placed slightly above the top of the plants, around 30 cm apart from each other with an angle of 25-40° between the optical axes of the cameras, and an angle to the floor of around 30^o to generate a top-view of selected branches and leaves. The overlap between the optical axes was created to improve quality of depth estimations. To remove the lens distortion in the images, images were calibrated and corrected using Vision Assistant 8.5 (National Instruments). Now, each pixel in an image could be translated in a vector in space with the camera centre as origin. For each series, two branches at the top of one plant were selected and blue markers with 8 mm diameter were placed at branches and leaves (Fig. 1A). One marker was placed at the start of a branch, and one halfway the branch, around the position where marked leaves were connected to the branch. Further, a marker was placed at four leaves situated at both sides of the branch. Actually, a tomato plant has composite leaves consisting of a large terminal leave and on average twelve lateral petiolate leaflets.

The branch and leaf motion were described according to Craig's (1989) manipulator kinematics theory. A coordinate system (frame) was attached to each of the branches and leaves. The axes of the coordinate system were defined according to the 'right hand thumb rule'. Each frame could rotate around its connection to a higher order frame (Fig. 1B). A main frame, which was assumed not to move, was defined for the plant stem. From two markers at the stem a vector was calculated which defined the orientation of the plant stem. It was assumed that this stem was perpendicular to the floor. The camera frame was rotated in the analysis in such a way that the plant stem became parallel to the z-axis of the frame. Further, the frame was translated to situate the marker at the main stem in the origin of the frame. With this centre and orientation of the main frame, sub-frames were defined for each of the tracked branches, and a sub-sub frame for each leaf. To define a sub-frame for a branch, a vector was created from the two branch markers. The positive x-axis of the sub-frame was placed parallel to the branch vector. The origin of this sub-frame was placed at the start marker of the branch. This is the connection point to the higher frame (main frame). It was assumed that rotation around the length axis of branches or leaves did not occur. This rotation cannot be measured with one single marker per object side. Based on the x-axis direction and with the assumption that rotation around the length axis of the object did not occur, it was possible to calculate the y- and z- axis directions, and from that, the orientation of the sub-frame. The same procedure was followed for each leaf. Motion of a branch or leaf was expressed as a horizontal (α) rotation around the z-axis of the frame, and vertical (β) rotation around the y-axis of the frame (Fig. 1B). In each image pair, the α and β angle of a frame (branch or leaf) with respect to its higher order frame (plant stem or branch) were calculated.

Position and orientation between the two cameras were measured in the greenhouse. Further, the position of two objects in the scene was measured with respect to the cameras and each other. From reconstructions of the scene it was found that there was inaccuracy in the measured camera angles and distances. They were difficult to measure in the greenhouse. A procedure was developed to determine camera position and angles from points in the scene. This was first tested with a camera set-up in the lab. The measured position and orientation of the cameras were optimized based on 9 to 13 manually selected objects within the images, and the measured distances between objects. The shortest distance between two vectors defining an object's position was calculated. This was done for all objects, and the shortest distances were added. Rotation matrix and position vector were varied until the sum of shortest distances for all selected objects in the scene was minimized. The measured distances of objects in the scene and the distance between the cameras were applied as constraints. In this way, a position vector and rotation matrix were calculated which defined the position and orientation of camera 1 in the coordinate system of camera 0. Quality of reconstruction was determined in the test set-up by reconstruction of objects with known dimensions. The procedure of minimizing shortest distances was applied for the series in the greenhouse. It was assumed that size of remaining errors in the greenhouse series were comparable to the remaining errors in the test set-up. Due to inaccuracy in reconstruction of camera position and orientation, an absolute position error of up to 18% could occur in reconstruction. This error is systematic and therefore eliminated automatically in the calculation of rotation angles α and β, which are based on relative displacement. The measurement accuracy of α and β was for both better than 1 degree.

Markers were extracted from the images after transforming the red, green, and blue image into hue, saturation, and lightness (HSL) colour space. A binary threshold was applied to the Hue-plane of this image. The resulting blobs represent the markers and the (x,y) pixel position of each marker was stored in an array. For the first image of a day, the marker arrays were manually sorted to create a corresponding sequence of markers for camera 0 and camera 1. For the following images, the marker with the shortest distance to marker *m* in the previous image, was identified as marker *m* at a new position. A maximum pixel distance was set to prevent that a neighbouring marker was identified as marker *m* when this marker was invisible due to for example over exposure. If no marker was found within the accepted distance, it was assumed that the searched marker was over exposed, and the previous location of the marker was stored in the new array.

From the pixel positions in the image pair, vectors were calculated defining the position of a marker. The vector of camera 1 was expressed in the coordinate system of camera 0. Two vectors defining a marker position may not cross for three reasons: inaccuracy in detection of the marker, inaccuracy in calibration and correction, and most important inaccuracy in the position vector and rotation matrix defining the camera position and orientation. For calculation of marker position from these two markers, the shortest line connecting vector 0 to vector 1 was calculated, and the position of start- and endpoint of this line were determined. The centre of this line was assumed to be the three-dimensional position of the marker.

Next to the image acquisition, vapour pressure deficit (VPD) was measured continuously and data on global radiation were available from the weather station at Bleiswijk. As vapour pressure deficit is one of the important factors influencing plant transpiration, it was tested whether vertical leaf motion (β) was related to VPD. The layout of the greenhouse was such that no extreme temperature gradient existed in the greenhouse. The ventilation was such that it did not affect the long term motion of leaves.

RESULTS

Separation of blue markers from the background and marker tracking were successful. In few cases miss-identification problems occurred as a result of over exposure. Figure 2 shows measured motions of leaves of one branch in α and β direction during three days of series 1. For this series, the maximum rotation of leaves was up to 10 degrees per direction per day. Branch motion was smaller with a maximum of up to 3 degrees per day. In α direction, a diurnal repeating pattern can be recognized for most leaves. All leaves move towards the main stem until 16:00 (increasing α). This motion stops or an opposite motion occurs from that time to the end of the day. Leaf 1 shows an increasing α from start to end of the three days. Each day, after an increase in angle from the start of the day, around 16:00 a stabilization or an opposite motion is visible. Leaf 2 shows a larger motion. When comparing start and end position of leaf 2 this leaf seems to move back to its "start position" during the night. Here again an increase until 16:00 is visible, with a decrease or stabilization after that moment. Leaf 3 shows small motions which is comparable to leaf 1, but does not increase its angle from the first to the third day. During the first night a decrease in angle is visible, during the second night no motion is shown. Leaf 4 shows the same pattern as leaf 2, but is smaller in its amplitude. During the second night, leaf 4 does not move, and motion during the third day differs from the other days.

In β direction, motion of all leaves is larger than in α direction. All leaves move up during the night, except for leaf 3. Motion of leaves 1 and 2 was very small. Leaf 1 shows a diurnal repeating pattern. From its start position, it moves down, with a stabilization around 16:00 and followed by a small upwards motion. Motion of leaf 2 is comparable to leaf 1, but leaf 2 moves slightly more. Leaf 3 does not move during the first part of day one. In the second part, it moves strongly up, and stays at this position during the night. The second day, this leaf does not move. The second night, it moves upwards, comparable to leaves 1 and 2. The third day, more motion is visible, but different from leaves 1 and 2. Leaf 4 shows a comparable but larger motion than leaves 1 and 2 during the first two days. The third day, this leaf is stable, with a small motion upwards.

In series 2 one high positioned branch showed much more motion. The branch showed a vertical motion of more than 15 degrees (Fig. 3, top) and leaves showed rotation of more than 40 degrees during the day (not shown). Visual inspection revealed that this branch also showed rotation around its length axis. Branch 1 shows a slightly decreasing β during the first two days. At the end of the day and during the night β increases somewhat. The first night this branch moved up, where it kept stable the second night. Branch 2 showed more motion than branch 1, with a strong decrease at the start of the first and second day, followed by an increase. A strong increase of angle β was visible at the end of each day. During the night this branch seemed to move back to its "start position". Both branches show more variation in their motion during the second day. Branch 1 and 2 show the same directions in motion, but amplitude of branch 2 is larger.

In Figure 4 graphs are shown with vertical motion of a branch as a function of VPD during the day. Graphs were created for two branches of series 2 for three days. Branch 1 was situated lower in the canopy, being the third branch from top. Branch 2 was situated at the top of the plant. Correlation value (R^2) for branch 1 was reasonable for days one and three (0.76 and 0.69, respectively), and small for day two (0.45). Correlation for branch 2 was small or non-existent for days one and two (<0.1). Despite this, it can be observed that during these days correlation exists for VPD values <3. Correlation of branch 2 was high for day three (0.9).

Figure 3 (bottom) shows radiation and VPD values of series 2. Radiation was strongly varying during day one and even more during day two. Radiation data were not available for part of day one which explains the interruption in this line. Day three was a bright day, with radiation strength as could be expected from the sun's altitude. VPD values were varying during days one and two, with most variation during day two. During day three, variation in VPD was small.

DISCUSSION

Resolution of used cameras was sufficient for the field of view of 95×71 cm at a distance of 0.5 m. Application of wide angle lenses allowed to track two full branches in one scene with small distances between cameras and tracked branches. Marker recognition and marker tracking worked good. Over exposure occurred in parts of images when radiation was strongly varying, but did not result in errors in the marker tracking procedure. When more markers per leaf or branch are desired, it can be considered to use two or more different colours for markers, or use unique marker targets (Frasson and Krajewski, 2010) to reduce the chance of miss-identification. Higher resolution cameras would be necessary when applying unique marker targets.

Despite the existence of an absolute estimation error, reconstruction was sufficiently accurate for the observed leaf motion (better than 1°, determined by measuring objects with known dimensions). When absolute position reconstruction of objects in the scene is desired, applying a stereo calibration package in combination with calibration objects could be considered. With the applied measurement method, rotation around the length axis of objects could not be recognized. Observations revealed that this rotation does occur.

Description of motion by attaching frames to leaves and branches worked well. Application of frames allows to express motion of a leaf with respect to its branch, but it is also easy to express motion with respect to the main stem, or for example the vector of sun radiation. Leaf motion graphs expressed in horizontal and vertical rotation were hard for people to translate into tangible motion in space.

From a comparison of correlation values to variance in sun radiation it was observed that during a bright day the correlation between vertical branch motion and VPD was well for both branches, and best for the high situated branch 2. During days with varying radiation values, the correlation for the high positioned branch 2 was very small. Radiation and VPD both strongly influence plant transpiration. Varying radiation distorts the relation between vertical branch motion and VPD. A top branch is strongly influenced by this variable incoming radiation, but little influenced by other factors. The radiation effect is smaller for a lower positioned branch. From another perspective, during a bright day, a lower positioned branch is influenced more by other factors than radiation, and radiation is less stable due to shadowing effects from higher positioned branches and leaves as well as the construction parts of the greenhouse. This could explain the lower correlation of branch 1 during day 18. These results also support the assumption that transpiration affects leaf movement.

CONCLUSIONS

The applied method was suitable for measurement of branch and leaf motion. Errors in measured angles were smaller than 1 degree. Motion of branches and leaves was described as a vertical and horizontal rotation around their connection to respectively branch or main stem, according to Craig’s manipulator kinematics.

During days with small variation in sun radiation, a good correlation between vertical branch motion and vapour pressure deficit was observed. This confirms the expectation that a relation between vertical branch motion and transpiration rate of a plant exists.

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Figures

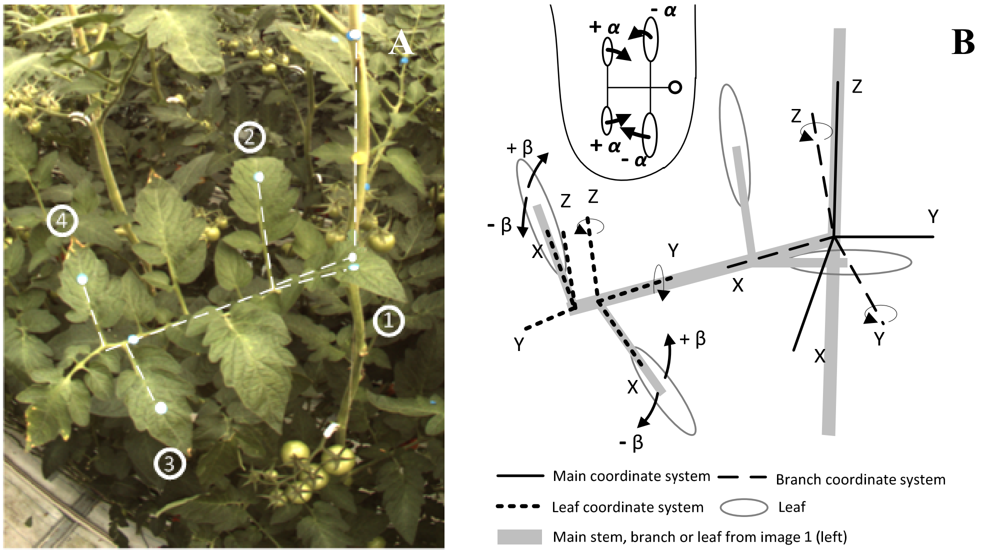

Fig. 1. A: Example of tracked branch and leave. Dotted lines indicate the skeleton which serves as base for description and calculation of rotation angles. B: Skeleton with main coordinate system (XY plane is horizontal, Z is vertical axis) and sub coordinate systems. For the branch coordinate system coincides the X-axis with the branch and for the leaf coordinate system coincides the X-axis with the leaf stem. Rotation around Y axis (β) and Z axis (α) were measured. (top) Top view with rotation directions in the horizontal plane: Rotation towards the main stem is valued as a positive α, independent of the position of the leave. α is rotation around Z axis.

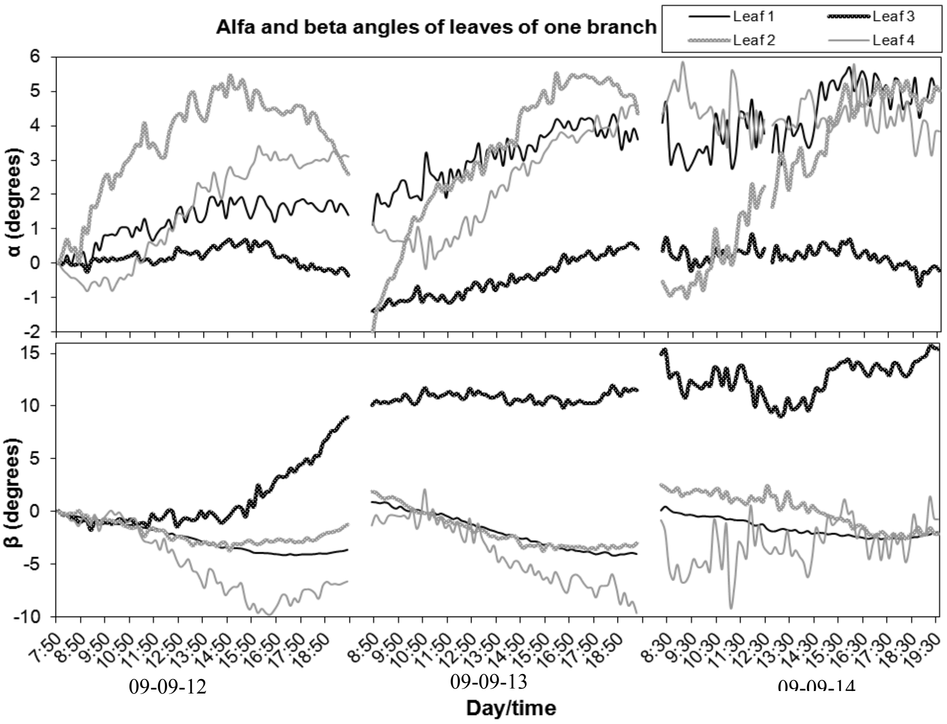

Fig. 2. Measured rotation angles of leaves of one branch in series 2. *α* for horizontal rotation and *β* for vertical rotation.

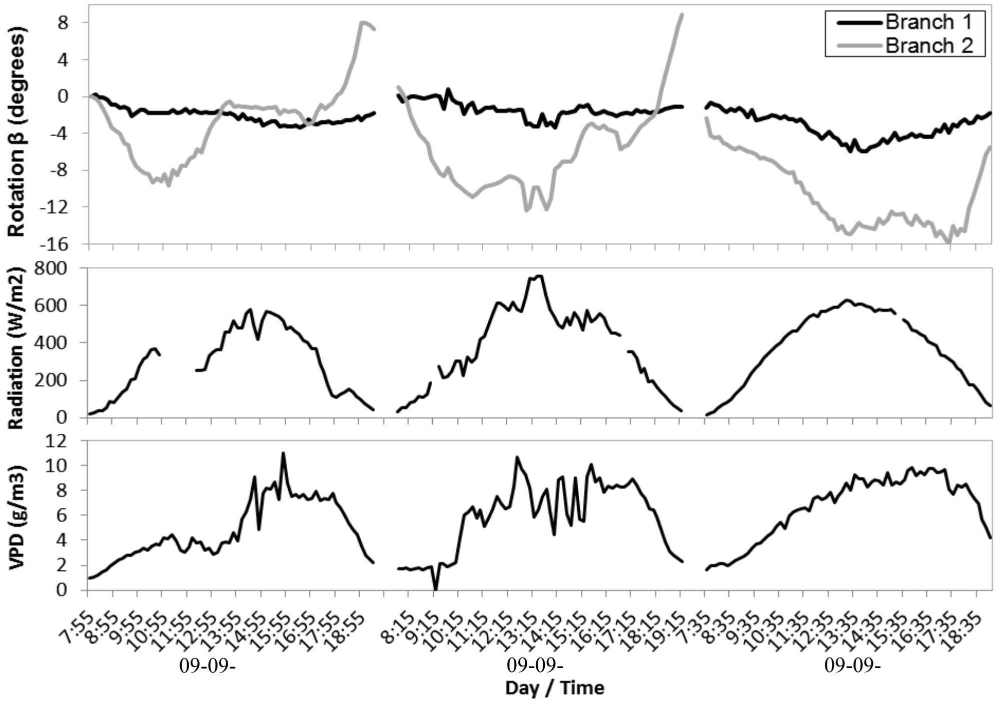

Fig. 3. Radiation, vapour pressure deficit and motion in beta direction of branches 1 and 2 during measurements of series 3.

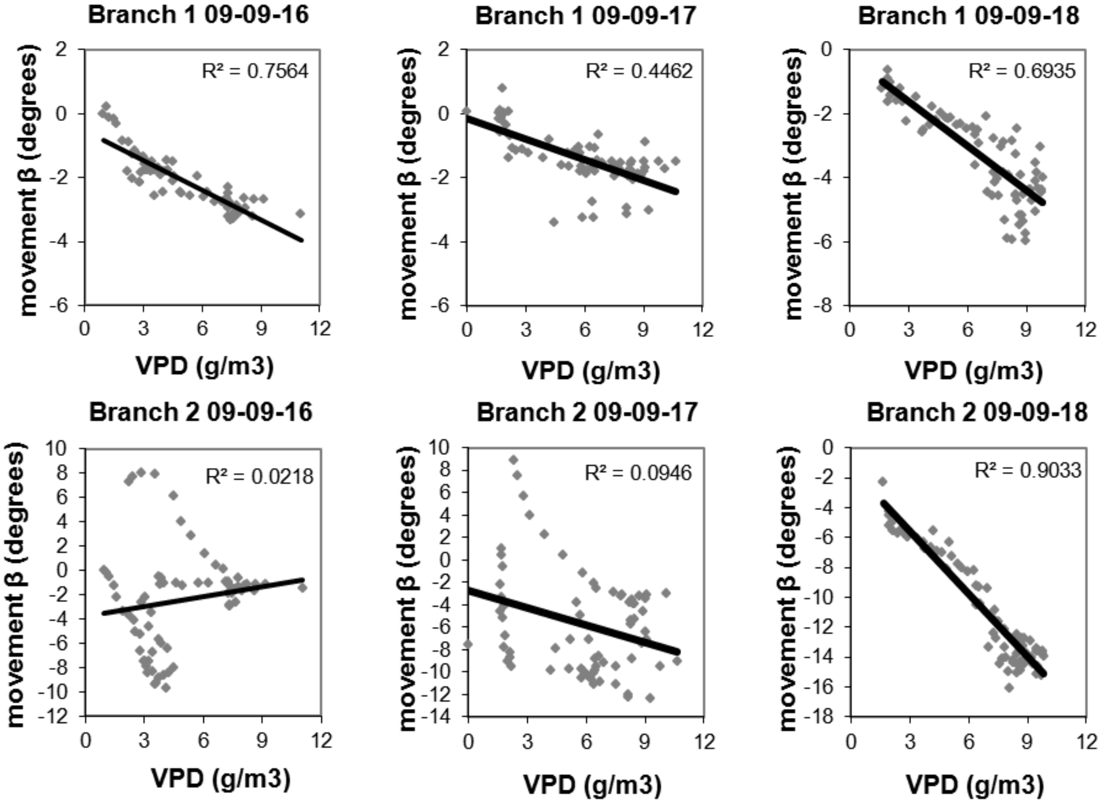

Fig. 4. Correlation of motion in β direction to VPD during three days of series 3 for branches 1 and 2.