Investigations on Usage of Multicopters in Greenhouses for Plant Monitoring and its Possible Side Effects

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Abstract

This study has set out to clarify the side effects of flying copters in greenhouses with a special focus on disturbances on plant growth and its vibration due to propeller turbulences. To achieve this, images of seedlings were taken then processed by image processing algorithms to find the optimum copter flying height in order to detect the finest details (leaves, stems etc.). The results hint that growth of basil plants could be significantly hindered by copter-based vibration and in case of using copters for monitoring tasks with sporadic flights, the risk of plant growth reduction is negligible. In conclusion, the side effects of using copters in greenhouses are visible on plant growth.

[Keywords] image processing, plant detection, vibration analysis, optimum flight height

I Introduction

1. Aerial crop imaging in greenhouses

Applications using UAVs (Unmanned Aerial Vehicles) are best suited to time consuming, dangerous and expensive inspections tasks. One could observe the fast development in use of aerial vehicles in infrastructure inspection (Alexis, 2017), security and military (Dietrich et al., 2017), search and rescue (Tarchi et al., 2017), transportation and delivery (Hochstenbach et al., 2015), and more vastly in precision agriculture (Duggal et al., 2016).

There are many opportunities to analyze crops and agricultural landscape. By attaching various sensors (hyperspectral, thermal, etc.) to these aircraft, one can achieve real-time / online information in a short time. Table 1 gives an overview of the used copters with their flight height and attached sensors in several agricultural investigations.

At the present time aerial imaging are done using UAV-board high quality cameras which require substantial drones to carry the payloads and there is an apparent lack of studies done on aerial imaging at low altitude or in greenhouses. Although practical image processing tools for plant analysis are available, it is clear that not all the mentioned investigations can be applied to a greenhouse setting. Therefore, the need for new concepts and active research into problems and strategies for low height flying copters is one significant challenge. Additionally, to achieve various applications such as climate control and plant monitoring in greenhouses with flying sensors one have to know quantitative numbers and the thresholds of turbulence effects on plants.

2. Alteration of plant growth by mechanical vibration

Manual crop mapping and plant analyzing are time consuming and labor-intensive tasks in greenhouses. Hence, to reduce the amount of man labor, multicopters with sensors flying at low heights could be used to retrieve crop information to optimize plant production. Low altitude flight might affect plants by vibrations due to wind turbulences caused by the rotating propellers.

In horticultural greenhouse production, growers often produce compact plants by using chemicals. It was discovered that wind also affects growth and the compactness of plants (Zhao et al., 2011). According to Mitchell and Myers (1995) vibration, shaking, touching or so called physical disturbances are altering to the growth, development and orientation of the plant. Plant growth reactions due to surface rubbing forces are negative due to the damage caused by the mechanical touches of the leaves or stems. On the other hand, the growth responds to periodic seismic (shaking) or vibrational disturbances which might be positive or negative. Studied shows so far that using shaking tables is critical due to the changes in soil structure and root construction damages (Loughian et al., 2014). Last but not least, biological processes such as photosynthesis and plant growth, might vary due to the changes in micrometeorological conditions such as hydrological transfers and soil moisture due to airflow and the stomatal sensitivity to air humidity may change due to the soil and air water content (Calvet, 2000). When taking all of these prior studies into consideration, the change in micrometeorological conditions and physical disturbance such as vibration caused by turbulences of low height flying copters in greenhouses might also...
influence plant growth. However, several aspects such as flying height, copter type or plant species should be taken into account. Nevertheless, until now, there is no literature available on the possible side effects of using copters in greenhouse to perform a copter-based applications.

3. Wind turbulence

In fluid dynamics, disc loading is defined as the average pressure change across an actuator disc such as rotors or propellers (Stepniewski and Keys, 1984). The difference in the air pressure produces wind. According to the Rotorcraft Flying Handbook (Federal Aviation Administration, 2000), disc loading of a hovering multicopter is defined as

\[ L = \frac{m}{A} \]  

where \( L \) is disc load (kg m\(^{-2} \)), \( m \) is total multicopter weight (kg) and \( A \) is rotor disc area, the area swept by the propeller (m\(^2 \)). Accordingly, for a given rotor disc area, the disc loading increases depending on the weight of the copter. Therefore, for copters flying at low heights, the copter size and the engine power are important factors in the resulting wind turbulences above the ground. Generally, it is necessary for indoor applications to work with low weight copters. On the other hand special cameras, electrical controllers and technical loads increase the weight.

II Objectives

The following investigation deals with the usage of copters as monitoring tools in greenhouse. For this, the turbulence effects of copters on plant growth should be analyzed and assessed.

The objectives have been divided into 3 steps:

1. Analyzing the vibration of plants caused by multicopter flight at different heights
2. Finding the ideal flying height for a multicopter to realize monitoring in greenhouses
3. Observing the vibration side-effects of multicopter turbulences on plants

III Materials and Methods

1. Multicopter

For all investigations a ready-to-use low weight quadeopter (Ar-Parrot 2.0, Parrot SA, France) was used. The original horizontal camera of the vehicle was changed to a vertical view (HD Camera: 720 P, 30 fps, 1 megapixels). The entire flight and imaging systems were controlled by an app (AR.FreeFlight, Parrot SA) through an android smart phone.

2. Plants, environments, setups and analysis

(1) Analyzing the vibration of plants caused by a multicopter flight at different heights

For experiments, monocotyledonous and dicotyledonous plants (Echinochloa, Matricaria, Beta, Amaranthus and Nicotiana) were seeded in pots and emerging were placed in boxes to create plant sceneries (randomly distributed without plant overlapping). To maximize the image contrast between the plants and their background the soil was covered with a thin layer of gypsum (Fig. 1).

Five different sceneries were created in this way for the investigations. In order to achieve information about the behavior of the leaves movement due to vibration caused by air turbulence, a RGB camera (EOS 600D, Canon Deutschland GmbH, Germany) was set at a constant position on a tripod close to the plant scenes. The angle of the camera was set in a
way that the maximum contrast between the plants and the white background can be acquired. For plant movement analysis 3 sceneries were chosen randomly and the leaf movement was recorded in a 1,080 p resolution at 30 fps while the copter was flying at seven different flying heights above the scenery (0.5 to 2.0 m, overall 420 images).

Afterwards, each series of images were overlapped using the software Halcon (MVTec Software GmbH, Germany) (Fig. 2).

The original images and the overlapped images were binarized by thresholding the blue channel. The shape area of the plants was calculated by counting the non-zero image pixels. To quantize the leaf movement for different wind forces (flying heights) a Leaf Movement Index (LMI) (%) was created. The calculation follows

\[
LMI = \frac{p - q}{q} \times 100
\]

where \( p \) is the possible shape area that the leaves can occupy due to the vibration (pixel) and \( q \) is the shape leave area without vibration (pixel). To avoid interactions between camera and turbulence effects, the camera was positioned beside the plants. That means the LMI always based on the view angle of 45 ° for every plant.

(2) Finding the ideal flying height for a multicopter to realize monitoring in greenhouses

The determination of the ideal or optimum flying height of the quadcopter was accomplished in a way such that the quadcopter camera can detect different plants with a critical size on the ground. Detection in this case means that plants could be separated from each other and from the background by a simple algorithm. For that we took the vibration of the onboard multicopter camera itself and the vibration of the plants due to the copter turbulences into account. Images of the artificial plant sceneries were taken at different flying heights from 0.5 to 2 m via the onboard camera, which was vibrating due to copter flight. For every specific height 5 pictures were taken. The number of plants per scene were counted in each picture with image processing and manually.

To realize the image processing, an algorithm using the HALCON tool (MVTec Software GmbH) was designed based on binarization with a fixed threshold of the green channel. Subsequently, the connected pixels were counted to approximate the number of detected plants per scene. The experiment was carried out under two main conditions:

a. Vibrated condition: In this situation both the plants and the camera had vibrations. Therefore images of the 5 sceneries were also taken from the flying quadcopter over the plants, which were vibrating due to the turbulences.

b. Flying camera and fixed plants condition: In this situation the vibrations of the plants were fixed to 0. To do so, high quality pictures of the 5 sceneries were taken and printed out. These prints were used instead of the natural sceneries to avoid plant vibration.

To quantize the success of plant detection, the following formula was used:

\[
SPD = \frac{n}{N} \times 100
\]

where \( SPD \) is the success of plant detection (%), \( n \) is the number of detected plants (detected with the camera on the flying copter and image processing) and \( N \) is the number of real plants (manually counted) in the scenery.

(3) Analyzing the vibration effects of multicopter turbulences on plants

The investigations were done in a greenhouse with fast growing sweet basil (Ocimum basilicum) in pots. The number of seeds per pot were randomly distributed (average 20 seeds per pot). The pots were placed on a greenhouse desk (24 cm spacing) in 8 rows and 28 columns. For each specific distance from the pot to the center of the experimental area at least 4 replications were available. To check the effect of the produced wind on the evaporation from the soil 28 pots with only substrate (without plants) were placed on the desk.

The temperature inside the greenhouse was set to 18 °C (night) and 21 °C (day) and in case of temperatures above 28 °C the windows would open. The plants were equally irrigated every third day with an ebb and flood system.

A multicopter model (equal to the drone used above) with four propellers was fixed above the center of the area (Fig. 3) at 1.2 m height (optimum flying height in the results of the experiment of chapter III 2.) above the pots. To simulate the original wind turbulences caused by a flying quadcopter, the propellers were controlled using a self-build hardware and software using the USB interface (U12, LabJack Corp., USA) and the ProfiLab-Expert software (ABACOM-Ingenieurgesellschaft, Germany). The control algorithm set all propellers to 2 min running time and afterwards...
to 8 min pause. This strategy was implemented 24 h a day. Therefore, the quadcopter was running 12 min h$^{-1}$ in general. The rotation direction of the propellers was the same as in the original flying mode.

The intensity of the wind caused by the running propellers was surveyed at different positions on the experimental area. It was measured in three perpendicular directions (x, y, z) by a thermal anemometer above the surface of the pots. One direction was set permanently as a straight line between the plant and copter, giving a direct flow of wind from the plant to the copter. The intensity of the wind was calculated as a vector length.

$$v_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$$ (4)

Where $v_i$ is the scalar wind speed at point $i$ (m s$^{-1}$) and $x_i$, $y_i$, and $z_i$ are the wind speeds in the three perpendicular directions at the same measurement point $i$, also in m s$^{-1}$.

To calculate the wind speed above every pot position on the table, an interpolation between the measured wind speed data were realized with the kriging algorithm. All of the wind speed data analyses were done with the program Surfer (GOLDEN SOFTWARE LLC, USA).

After 14 d of cultivation the maximum height, fresh weight and dry weight of the plants in every pot were measured. From the pots placed in rows D and E (Fig. 3) the number of plants per pot, number of leaves, leaf area, fresh leaf weight, stem height and upper internodes height were measured. The empty pots were weighted every 3 d. Leaf area measurements were done by image processing. All height measurements were applied manually with a ruler. The statistical analysis of the data was realized with R version 3.4.3 (R Core Team, 2017). The data were checked for normality of the distribution. Afterwards an ANOVA test was conducted.

(4) The relation between flying intervals and plant growth effects

In this experiment 6 multicopters were fixed at 1.2 m (optimum flying height in the former experiment) above 16 basil pots in the center of 6 sceneries. These were made up of sections called growing boxes and were separated with 6 transparency films and equipped with artificial light (Fig. 4). Therefore, all the plants in one box formed a plant group with a specific multicopter treatment. Six different treatments were designed. They were set to 20, 10, 5, 2.5, 0.05 and 0 % copter running time within a 10 min cycle. This strategy was implemented 24 h a day. Every week the plant groups and their treatments were moved to another box, to achieve similar growth conditions for every group.
For analyzing the growth after 2 weeks, images were taken with a high-resolution camera from two different horizontal views (90° variation), facing the plant pots.

The height of the plants were calculated by image processing with the HALCON tool (MVTec Software GmbH) by measuring the outer rectangle of the plants (Fig. 5). In addition, to consider the bending effects of longer seedlings a correction formula was used. The height of a plant \( H \) in pixel with or without bending was calculated by:

\[
H = \begin{cases} 
\frac{A_p}{X_{rec}}, & X_{rec} < X_{pot} \\
\frac{A_p}{X_{pot}}, & \text{else} 
\end{cases} 
\]

where \( A_p \) is the plant area (pixel), \( X_{rec} \) is the width with bending and \( X_{pot} \) is the width without bending.

IV Results

1. Analyzing the vibration of plants caused by a multicopter flight at different heights

Figure 6 represents the movement of the leaves due to the vibration while the quadcopter was flying at 0.5 m altitude. Overlapping 20 images shows the possible area that one plant occupies within the experiment.

Figure 7 shows the maximum and minimum range for the Leaf Movement Index (LMI) while the quadcopter is flying at different altitudes above the plants.

From Fig. 7 there is a clear connection between quadcopter height and leaf movement, as the quadcopter flies at lower levels the leaf movement becomes greater. A flying height of 0.5 m results in a LMI of up to 100%. This means that the total area which a leaf or a plant occupies is double and therefore plant monitoring with image processing will lead to significant errors.

2. Finding the ideal flying height for a multicopter to realize monitoring in greenhouses

Figure 8 represents the results of the plant detection via the quadcopter at different flying heights and vibration settings.

The results give hints that flying height reduces the plant
vibration error. Figure 8 (a) shows the success of a plant separation done by copter based image processing using fixed (printout) plants. One can see that higher flying distances from the ground result in a linear increase of the image processing errors due to the decreased resolution of the camera. But taking into account the resolution of the camera, the turbulences of the quadcopter and the flying height together it shows that a minimum plant detection error occurs if the copter is flying at less than 1.2 m (Fig. 8 (b)). Correspondingly, due to the biological objects, the data show a higher variance comparing with fixed plants used in Fig. 8 (b). Depending on this result, the decision was made to use the quadcopter at a flying height of 1.2 m above the plants in the next experiments.

3. Analyzing the vibration effects of multicopter turbulences on plants

The modeling of the wind intensities and directions at different positions of the experimental area is shown in Fig. 9. One can see that the wind speed under the propellers set at 1.2 m height above the pots (optimum flying height in the results of the experiment of chapter III 2. (2)) reaches the values up to 2.6 m s\(^{-1}\) at plant level. The spatial wind distribution is more or less circular concerning the projected center of the quadcopter. This indicates that the control of the fixed copter propellers reached a high accuracy level. Also the figure of the wind vectors confirms this outcome. At the edges of the desk the wind measured only 0.1 m s\(^{-1}\). This means that more or less there was no wind affect.

Figure 10 shows the same data from Fig. 9, but the wind speed is related to copter-table distances. Because of the circular wind speed distribution on the table, one can fit the values to a 6 grade polynomial function of:

\[ W_s = \sum_{i=0}^{6} b_i x_i \tag{6} \]

Where \( W_s \) is the wind speed (m s\(^{-1}\)) and \( x \) is the distance of the pots from the projected copter on the table.

One can fit the values to a 6 grade polynomial function because of the circular wind speed distribution on the table. With this function the average wind speed \( W_s \) on every position on the cultivation table could be calculated and used for further biological analysis.

Figure 11 shows the results of the plant measurements and the measurements of the pots without plants based on calculated wind speeds. One can see that the evaporation of the empty pots is mostly influenced by the wind turbulences generated by the quadcopter (Fig. 11 (b)). Increasing the wind speed from 0.2 to 1.74 m s\(^{-1}\) doubles the soil evaporation. In addition, the plant height shows a clear effect depending on
the wind speed. Particularly the high wind speed directly under the copter leads to significantly smaller plants ($p \leq 0.001$, ANOVA test). The copter turbulences have no statistical effect on fresh leaf weight, number of leaves, leaf area and proportion of height of the internodes to height of the stem (Fig. 11). The few outliers in Fig. 11 were maybe due to the different plant varieties of basil.

4. The relation between flying intervals and plant growth effects

Figure 12 shows significant differences in plant heights $H$ and effects in (a) and (b) are highly significant. Effects in (c), (d), (e) and (f) have no significant differences ($p \leq 0.001$, ANOVA test).

Fig. 11 Wind effect on basil pots after 2 weeks

(a) Height of the plant
(b) Water evaporation from the soil
(c) Fresh leaf weight
(d) Number of leaves
(e) Leaf area
(f) Proportion of height of the internodes to height of the stem
if the propellers were running more than 2.5% (of a 10 min cycle). One can see that a significant reduction in plant height occurs between 0.05 and 2.5% of the running time of the propellers.

\[ p \leq 0.050, \text{ANOVA test} \]

The wind speed distribution under the copter shows a significant different between the control (0% running time of the copter above the plant) and the maximum running time of the propellers (20%).

Fig. 12  Plant height and significances depending on vibration cycle times after 2 weeks

V  Evaluation

In addition to the challenges presented in literature from outdoor drone usage, employing the use of copters in greenhouses present new challenges such as air turbulence and micrometeorological and physical disturbance. From this study, it can be stated, that for a quadcopter to capture clear images in greenhouses while minimizing the vibration effects due to resulting turbulence, the ideal flying height is around 1.2 m. Attaining high quality images is dependent on the resolution of the onboard camera and the vibration sensitivity of the plants. Naturally, by adding high-resolution cameras to a copter one can achieve better results in plant separation or monitoring. However, adding extra weight to low weight copters is detrimental due to increased disc loads (Federal Aviation Administration, 2000). Consequently, better resolution cameras or special monitoring issues on the onboard camera system require bigger drones, which produce more turbulence and need higher flying heights. Additionally the vibration of the camera itself contributes to undesired effects (Crete et al., 2008). Therefore, the flying height is one important factor in copter monitoring in greenhouses. It is clear that the optimum flying height is dependent on the monitoring task, the plant species, the growing stage and the copter itself. Finally, in any case, it is difficult to reach a leaf movement index lower than 50% (due to the vibration caused by the propellers) by flying a multicopter in a greenhouse at a calculated ideal height. This means, if the spacing between two leaves is less than half of its area, one cannot do copter based imaging without having overlapping problems.

Further the investigations show significant wind disturbance if copters are used at low heights in greenhouses. Finnell (1928) observed morphological changes in plant height, size and thickness of leaves caused by wind. In our investigations the stress caused by the vibration appears in lower plant growth rates. Additionally Penman (1956) states, that there is more evaporation from the soil when wind is present. He also mentioned that if potential evapotranspiration is high, soil water potential must be maintained at a higher level. Otherwise, the soil cannot supply water fast enough and this results in plant stress. Figure 11 (b) supports this statement since at different distances from the quadcopter we found significantly different water contents in the soil. Therefore, the growth reductions caused by turbulence could be based on physiological effects depending on direct plant vibration, or that the growth reduction is caused by evaporation changes and water stress. The vibration of the plants is also in direct relation with the species, the wind force and the duration of the wind. Thus our findings could not be generalized to other species or other copters, but we showed that plant growth reduction is a possible side-effect when copter-based applications are running in greenhouses. But to either reach or avoid this side-effect, a numerous number of copters are needed and running time must take into consideration.

The settings of the flight simulation (fixed copters) in the growing boxes were comparable to an original flight, because the same propellers and the same rotating directions were used in comparison to the original quadcopter. To see plant growth reduction effects, we have also concluded that the copter based vibration time must be longer than 5% of the overall time in 24 h. Nevertheless, in the cases that no change in environmental condition is desired and depends on various applications performing by the copter inside the greenhouse, altering plant growth is neglectable if its running time is less than 2.5% of the overall time in 24 h. Additionally, the wind speed distribution under the copter (Fig. 12) leads to the assumption that one copter can influence 1 m² of plants at a given time. Putting all factors together induce a calculation where 1 copter per 50 m² can affect the height. Looking at the available copter generation today, mini copters do not seem to have a noticeable problem to realize plant manipulation.
VI Conclusion and Future Work

We can conclude that it is necessary to consider plant vibration due to turbulences if copters are used in greenhouses for plant monitoring. The optimum flying height in our set up was 1.2 m above the plants. Leave movements of 50% of their area are normal and should be taken into account if image processing tasks should be solved.

For basil plants we found significant changes in growth rates and evapotranspiration caused by propeller turbulences. Therefore, we can conclude that plant regulation / manipulation is the side effect one might face by means of copter applications in greenhouse. Nevertheless, to realize drone-based applications inside a greenhouse in future, one must consider attaining an autonomous flight of the drone. Maintaining at the accurate position and orientation is one essential primitive to accomplish this task. To attain autonomous flight, the drone needs to continuously perceive information over its position, plan a path and execute the commands. Therefore, based on the time the drone needs to maneuver over a desired point autonomously with the sporadic flight, the risk of occurring side effects such as plant growth reduction shall be considered realistic.

On the other hand, if the duration of the flight above the plants is not long, one would very much benefit using copters in the greenhouse to achieve climate data sensing and to monitor the plants.

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