TOWARDS AUTOMATED PNEUMATIC THINNING OF FLORAL BUDS ON PEAR TREES

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ABSTRACT

Thinning of pome and stone fruit is an important horticultural practice that is used to enhance fruit set and quality by removing excess floral buds. As it is still mostly conducted through manual labor, thinning comprises a large part of a grower's production costs. Various thinning machines developed in recent years have clearly demonstrated that mechanization of this technique is both feasible and cost effective. Generally, these machines still lack sufficient selectivity to take into account the specific fruit bearing capacity of each tree. Furthermore, the current devices often cause damage to shoots, leaves and fruitlets which makes the trees more susceptible to dangerous diseases such as fire blight (*Erwinia amylovora*) and cankers.

To address these issues, we investigated a new non-contact way of thinning using pulses of compressed air in combination with a sensor capable of detecting the floral bud distribution. This way, the thinning efficiency can be improved by providing real time information of the floral bud distribution. We focused on the early phenological stages (until bloom) of the pear cultivar *Conference*, for which there are few chemical thinning alternatives.

The forces required to remove a floral bud were measured in a laboratory test bench. These required forces change as a function of bud development. A pneumatic setup was built and tested during a two-year trial in an orchard to determine the effects of air pressure, nozzle type, distance and phenology on the attainable removal efficiency. Hereafter, a performance model was built using stepwise logistic regression modeling. Thinning grades as high as 93.13 % and 74.52 % could be achieved for, respectively, a dry and a wet season. Furthermore, pneumatic thinning was observed to reduce tree damage to a minimum since floral buds were removed at their natural breaking point, i.e. the pedicel abscission layer.

Besides this, we developed a multispectral vision sensor capable of detecting floral pear buds during the phenological stages before bloom. During two flowering seasons, scenes were captured in the orchard at six distinct optical wavebands in the visible and near infrared region of the spectrum. Measurements were conducted under controlled illumination. Using canonical correlation analysis, a spectral discrimination model was built that recognizes pixels originating from floral buds. Hereafter, an image analysis technique was developed to translate the pixel classification to object recognition. This algorithm was able to recognize more than 80 % of the floral buds that were captured under proper illumination. Therefore, the multispectral sensor can be used to increase the efficiency of pneumatic thinning or other thinning machines. Furthermore, it can as well be used independently for early-season yield estimation.

Keywords: Fruit thinning, Mechanization, Pear, Pneumatics, Multispectral imaging, Feature detection, flower buds

INTRODUCTION

Fruit trees have a natural tendency to produce crop loads distributed over many fruits (sinks). This often results in the production of many small fruits which are not suited for fresh market sale. Thinning decreases the competition for photosynthetic products by removing the excess buds, flowers or fruitlets. This not only allows the remaining fruits to reach commercially interesting sizes but also increases fruit quality, tree vigor and yield regularity (Lopez, 2011; Theron, 2010 and Meland, 2009). Research has shown that early thinning – at or even prior to bloom – leads to stronger positive effects than the traditional late season thinning because it minimizes the investment of the trees in fruits which will not be harvested (Theron, 2010; Meland, 2009; Link, 2000; Bertschinger, 1998). Together with pruning and harvesting, thinning is one of the most labor-intensive cultivation measures as it is typically still performed by hand.

Over the years, the potential of chemical thinning has been extensively studied. It can be considered a practical and cost-effective method, but it cannot completely and reliably replace hand thinning (Miller and Tworkoski 2010). There are two main drawbacks: the efficacy of the currently available thinning agents is strongly related to cultivar and environmental conditions (Kviklys and Robinson 2010; Peck and Merwin, 2009) and chemical thinning often has detrimental effects on the environment, tree vigor and human health (e.g. laborers). For this last reason many chemical thinning agents have been withdrawn from the market (Costa et al. 2013). Even under perfect conditions, chemical thinning offers no direct feedback or response and growers have to wait or postpone further treatments.

It is no wonder that automated thinning can be considered a viable and economically feasible alternative for the traditional methods. String type thinners perform apple and peach blossom thinning by means of fast rotating flexible strings (Seehuber et al., 2013; Martin-Gorriz et al., 2011; Baugher et al., 2010). Spiked drum-shakers do peach fruitlet thinning by using rotating drums to transfer vibrational energy to the canopy branches (Miller et al., 2011). Yang (2012) and

Nielsen et al. (2012) developed a prototype robotic manipulator and clamp-like end effector for brushing off peach blossoms. Other techniques such as trunk shaking (Gloser and Hasey, 2006) or limb shaking (Rosa et al., 2008) were found less effective.

Positive results were realized by these automated techniques, but their thinning speed and efficiency need to be further improved by taking into account the tree-to-tree variability. The floral bud distribution is non-uniform throughout an orchard and some trees – or parts of a tree – will undergo less or more severe thinning than required. Excessive thinning should be avoided. Also, most of the existing techniques often cause injuries to shoots, leaves and bark. Therefore, a thinning action tailored to the needs of each individual tree would prevent unnecessary tree damage. This maintains tree vigor and reduces the risk of disease spread (Kon et al., 2013; Ngugi and Schupp, 2009).

In recent years, several researchers have investigated vision systems to detect and quantify fruit blossoms with the goal to provide this information as feedback to a thinning machine to increase selectivity. Gebbers et al. (2013) mapped the flower density on apple trees by a stereo camera platform and used this information to control the rotation speed and thinning intensity of a string thinner. Nielsen et al. (2012) used a trinocular stereo color camera to locate the three dimensional (3D) position of the peach blossoms with a spatial accuracy better than 1 cm. Emery et al. (2010) developed a scanning laser range imaging system to measure the 3D shape of peach trees with a spatial accuracy of 1.2 cm.

These detection techniques all rely on the sharp color contrast between the blossoms and their environment and are based on standard RGB cameras. However, this approach is less suitable for detecting floral buds prior to bloom as the brightly colored petal leaves are still contained within the buds. To our knowledge, no attempt has been made to develop a sensor to detect floral buds prior to bloom.

Multispectral imaging can be successfully applied for object recognition in many agricultural applications (e.g. Bas et. al., 2013; Bulanon et al., 2010; Okamoto and Lee, 2009). This technique produces images with a high contrast between objects of interest by benefiting from differences in spectral characteristics which are not necessarily observed in the red, green or blue regions of the spectrum. Wouters et al. (2013) determined the optimal wavebands for building a multispectral vision system which is able to detect floral pear buds in the phenological stages before bloom (*Pyrus communis* cv. *Conference*). With these wavebands, a discrimination model was built that showed good pixel classification under laboratory conditions (i.e. 95 % correct pixel classification). However, additional steps are required to make this technique suitable for floral bud detection under field conditions.

The work described here aims at the most important of these issues for flower bud thinning, starting with a detection system in the field followed by a novel air-pulse based thinning method. It requires a new multispectral setup with a new pixel classification model and followed by image analysis for correct object detection (flower buds and other tree parts). This setup was tested in field trials.

Avoiding direct physical contact between the fruit trees and the thinning machine can reduce the risk of tree damage and subsequent spread of diseases. Therefore, another objective of this research was to investigate the potential for pneumatic removal of floral pear buds. This is based on the required forces to remove floral pear buds of the cultivar *Conference.* A prototype concept of pneumatic thinning was designed and tested.

FLORAL BUD DETECTION

A mobile camera platform was designed and built to perform multispectral measurements in a pear orchard [Fig. 1.(a)]. The setup consisted of a 12 bit monochrome CCD camera (TXG14NIR, Baumer, Frauenfeld, Switzerland) with a resolution of 1392 x 1040 pixels and a 16 mm mono-focal manual iris lens (C1614A, Pentax, Tokyo, Japan). A fast rotating multispectral filter wheel (FW103H/M, Thorlabs Inc, Newton, NJ, USA) was placed in front of the lens. It housed six optical band-pass filters in the range 400-1000 nm with a diameter of 25 mm. These filters were rotated sequentially in front of the lens with a change time of approximately 55 ms between adjacent filters. This enables fast multispectral measurements (< 1 s) with virtually no distortions between the different filter images, e.g. motion blurring caused by wind. The filters were commercially available band-pass filters and were selected to have band-pass regions that match as closely as possible the desired optimal wavebands to discriminate between floral buds and their environment (Wouters et al., 2013). The transmission bands of the filters are displayed in Table 1.

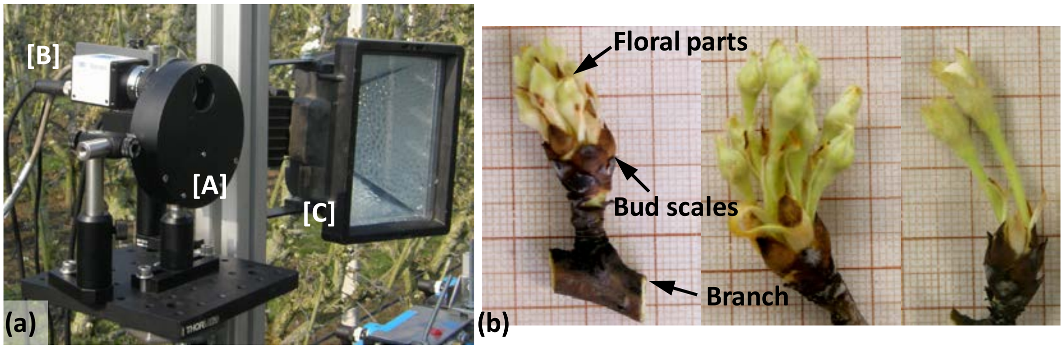

Fig. 1. (a) Camera platform used during the field measurements. Main components are: [A] fast rotating filter wheel, [B] monochrome camera and [C] halogen light source. (b) Appearance of the floral buds during the examined phenological stages. The three main constituents are indicated. Stages are displayed chronologically, from left to right: “Green cluster”, “Green bud” and “White bud”. The buds are displayed in front of graph paper to give a measure of scale (1 square = 1 mm).

Table 1. The bandwidth of the waveband filters used during the field experiments.

Relative importance[1]	Waveband [nm]	Filter name
1	589 – 625	NT84-102[3]
2	925 – 975	NT86-072[3]
3	430 – 490	MF460-60[2]
4	672 – 712	NT67-038[3]
5	752 – 798	NT84-106[3]
6	532 – 554	NT67-032[3]

1 as determined by Wouters et al., (2013)
2 manufactured by Thorlabs Inc, Newton, NJ, USA
3 manufactured by Edmund Optics, Barrington, NJ, USA

With this setup, a two-year field trial in a commercial *Conference* orchard was set up. Measurements were conducted at nighttime to avoid that the recorded images would suffer from varying illumination related to weather conditions. Furthermore, measuring at night simplified the observed scenes as the visibility of background objects was greatly reduced. Multispectral images were recorded at random locations throughout the orchard. Before each measurement, the setup was placed at a distance of approximately 1 m from the canopy which yielded a field of view of 410 by 550 mm. The height at which the setup was placed was chosen randomly as well. Illumination of a scene was provided by a 500 W halogen lamp. For the purpose of data normalization, an optical reference was placed in the field of view of the camera. In the first testing season this was a small white polytetrafluoroethylene (PTFE) plate. Due to its brightness this reference often resulted in saturated images. Consequently, it was replaced in the second season by a grey-colored reference made from polyvinylchloride (PVC) which possessed a luminosity similar to that of the trees in a scene. Both PTFE and PVC display stable optical behavior in VIS/NIR range without clear absorption peaks.

The different pre-bloom phenological stages during which the camera system was tested are given in Fig. 1.(b). They range from “Green cluster” to “White bud”. In total, over 600 floral buds were imaged. The mm-graph paper background gives information about the size of the flower parts. The different components of interest in the images are floral parts, bud scales, tree support sticks (not shown) and the bark of branches or trunks.

For the detection of these different objects in the images, a pixel discriminant model was created by means of canonical correlation analysis (CCA), as described by Sharma (1995). CCA is a multivariate analysis technique which produces orthogonal discriminant functions that have maximum separation between groups. Three discriminant functions are required to discriminate between the four main components. In the discriminant space spanned by these functions, pixels were classified by means of their Bayesian posterior probability. Finally, a probability image P was made for each scene by assigning to each pixel the posterior probability of it belonging to the group “flower parts”. Individual pixels were subsequently grouped into objects by a custom detection algorithm.

Because the CCA-procedure was conducted based on only the four main components, pixels originating from other objects were necessarily assigned to one of these groups as well. This had a negative effect on the quality of P. As a remedy, pixel observations were filtered based on the confidence intervals of each group in the discriminant space spanned by the first two discriminant functions. The confidence intervals were calculated by means of the covariance matrix of each group.

The performance of the detection algorithm was validated in two ways. First, the multispectral images captured during the first growing season were subjected to a three-fold holdout cross-validation (*type A*). In this analysis, the multispectral images recorded during the first testing season were divided by growth stage into three groups of approximately 15 scenes each. For each step of the cross-validation, the data of two groups was used for training and optimization of the detection algorithm, whereas the remaining group was used for validation. The second way of validation (*type B*) was conducted similarly, but all data of the first and second growing season were used as training and validation set, respectively.

The performance of the algorithm was described by means of the true positive rate *TPR* and the false detection rate *FDR*. Both ratios are given by the following equations:

$$TPR = \frac{TP}{TP + FN} \tag{1}$$

$$FDR = \frac{FP}{TP + FN} \tag{2}$$

TP represents the number of correctly detected buds (true positives), while *FP* represents the number of false detections (false positives). *FN* is the number of undetected buds (false negatives). These ratios were chosen because, as in many object detection problems, no true negatives could be defined. *TPR* was defined as the fraction of floral buds which were correctly detected while *FDR* represents the number of false detections relative to the number of actual floral buds. In order to have a high performant algorithm, it is clear that *TPR* should be close to 1 whereas *FDR* should have a value near 0.

For the type A-validation, similar results were obtained for both training and validation. The detection algorithm was able to correctly recognize approximately 83% of the floral buds with an average *FDR* of 22%. For the type B-validation, all the data of the first season were included in the training set, improving the classification results – for the training set – slightly, i.e. a *TPR* of 84%, and a *FDR* of 14%. For the validation set, the *TPR* value was somewhat lower at 78% but still a low *FDR* of 14% was realized. Most of the false detections could be attributed to the occurrence of (large) leave buds, especially during the “White bud” stage when these buds started opening. Other false detections were caused by small noisy regions in the probability image which resembled a floral bud. Finally, in a few cases, parts of the white PTFE reference, plastic wires or floral buds located in the background were falsely classified as foreground buds. Irrespective of the detection system used, a part of the floral buds is expected to be occluded due to their semi-random location on the trees.

DETACHMENT FORCES OF FLORAL BUDS

The breakage behavior of floral pear buds (cv. *Conference*) was investigated during two flowering seasons for twelve early phenological stages, starting from dormancy to the end of bloom. To this end, 26 two-year-old potted-trees (14 in 2010 and 12 in 2012), were used for sampling. 483 floral buds – approximately 20 floral buds per stage per year – were collected randomly from the trees by cutting them off well below their attachment point on the branch. Hereafter, the buds were subjected to a tensile test on a universal testing machine. The buds were aligned in such a way that the axis of the pedicel supporting the bud coincided with the axis of measurement. The top end of the bud and the supporting branch were clamped sufficiently far from the expected failure point. After each measurement, the diameter of the fracture surface was measured with a caliper. The resulting force-displacement curves were used to determine the detachment force ([N]), from which the fracture strength ([MPa]) of each floral bud was calculated. Nearly every floral bud had fracture occurring at the pedicel abscission layer below the buds, independent of the phenological stage.

The detachment force was significantly different for the two seasons ($p \leq 0.05$) with respective average values of 6.65 N in 2010 against 9.95 N in 2012. This was due to difference in the size of the buds. However, from a two-factor ANOVA model of the fracture strength, it was concluded that the main effect of “season” as well as its interaction with “phenological stadium” were not significantly related to the fracture strength. Therefore, the fracture strengths were pooled over the two years and were considered as only a function of the phenological stage.

Shortly after the end of dormancy, the fracture strength shows a decreasing trend, with a minimum reached at “Green cluster”. Hereafter, an increasing trend is observed. This larger fracture strength might be a result of the increasing weight and volume of the buds as flowers are developed.

Apart from the fracture strength, the optimum period for pneumatic thinning also depends on the surface area of the buds. As the latter increases, the resulting force of a compressed air pulse on the buds increases as well. This effect partially compensates for the increase in fracture strength towards bloom. Therefore, pneumatic thinning seems most viable starting from “Green cluster”.

To our knowledge, no prior research has been done regarding the fracture strength of pre-bloom floral buds.

PNEUMATIC THINNING EXPERIMENTS

A setup for generating targeted air pulses was built for field trials. The system was designed to be powerful enough to overcome the detachment force of the floral buds, as determined in the tensile tests.

In the pneumatic circuit of the experimental setup, compressed air was provided by a mobile gasoline engine powered compressor with a 40-litres air tank. In addition, a reservoir with a capacity of 10 liters was used as an air buffer just in front of the outlet to guarantee sufficient air flow and pressure. During the pulse, compressed air passed through a service unit containing air filters and a manual pressure regulation unit. In order to generate air pulses of the desired duration, a fast switching double solenoid valve was used. This valve uses internal pilot air and has a response time of 16 ms. The inside diameter of the supply lines was chosen to be large enough to prevent choking of the airflow as to avoid a limitation of the blowing force. Both actuation of the valves and data acquisition were managed by a software program written in Labview 2009 (National Instruments, Austin, Texas, USA).

Air pulses were created by switching the valve "on" and hence discharging compressed air into the environment. The force generated this way on an object depends strongly on the exit speed of the air. The efficiency of converting pressure into kinetic energy was increased by placing an air nozzle at the system exit. Two nozzle types were tested: a flat shaped nozzle and a round type nozzle. In laboratory experiments, the blowing force and divergence of the air jet was tested and it was found that this remained acceptable up to a distance of 40 cm. The nozzles were mounted on a support that could be fixed to the ground.

Thinning experiments were conducted by aiming the nozzle from a selected distance at the geometric center of a randomly selected floral bud. The orientation of the flat-shaped nozzle relative to the floral buds was random. The air pressure was set via the manual pressure regulator. An air pulse with duration of 500 ms was fired at the chosen floral bud. A thinning attempt was considered a success when at least one of the reproductive organs of the floral bud was removed or irreversibly damaged.

The experiments were performed in a commercial pear orchard during six consecutive early phenological stages of the pear cultivar *Conference*, ranging from "Mouse ear" to "Full bloom". To verify whether pneumatic thinning is also applicable during the conventional period of manual thinning, some tests were also conducted on fruitlets, approximately 35 days after full bloom (DAFB). It was not feasible to conduct experiments for every possible combination of distance and supply pressure.

The outcome of every experiment was considered either a success or a failure, and thus the chance of success p follows a binomial probability distribution. For this reason, p was modeled via a backwards stepwise logistic regression (Kleinbaum and Klein, 2002). This technique allows for the selection of a set of significantly important independent variables that together explain a large part of the total variation of the observed outcomes. In the logistic regression model the thinning success is described as a function of the supply pressure, working distance and phenological stage.

In total, – distributed over the different test conditions – 543 out of 1135 floral buds were successfully thinned. A round-shaped nozzle was found to be more efficient than the one with a flat geometry. The highest achievable thinning rate was found to be 93.13 % in the first season (dry weather) and 74.52 % in the second season (wet weather). This difference in performance was most likely caused by the different environmental conditions and biennial bearing effects.

In the stages up to and including "Full bloom", floral buds were removed in their entirety in 94.11 % of the successful thinning attempts.

It was also observed that the highest success rates were achieved on the older more rigid wood of the trees. The two-year-old wood, which occurs mainly at the top and bottom of the canopy, was much more flexible and was therefore able to absorb some of the kinetic energy of the air pulses, which reduced their efficacy.

No damage to shoots or bark was observed during the experiments. However, the pulses sometimes caused damage to the few young leaves present during the early phenological stages, but this damage was comparable to that of naturally occurring events such as wind and rain.

In the fruitlet stage, clusters of fruit appear per floral bud. At that time, the percentage of completely removed buds (all fruits per bud removed) dropped to 52.63 %. In case of the remaining 47.36 %, usually one or two fruitlets per cluster were removed. At the fruitlet stage the trees had developed a full canopy of leaves and the thinning method tended to damage or remove a major part of the leaves around the fruitlets.

A significant interaction between “phenological stage” and “distance” was found, as well as between “distance” and “pressure”. The performance of pneumatic thinning increases at shorter distances and higher supply pressures. The system has to work fairly close to the canopy making it more suited for use in training systems with a structured canopy. Depending on the chosen settings – particularly during the very early phenological stages – small deviations from the desired working distance can considerably affect the degree of thinning.

SUMMARY AND CONCLUSIONS

In this work we demonstrated the feasibility of detecting floral pear buds during the early phenological stages by means of a multispectral camera system. A custom image analysis algorithm was developed which was able to detect the majority of the floral buds with a low false detection rate.

Though these results certainly are encouraging, it is expected that the performance of the detection algorithm can still be further increased by tuning the parameters specifically for each phenological stage. This especially applies to the “White bud” stage where the development of the leave buds resulted in an increased rate of false detections. Furthermore, it would be interesting to check whether good floral bud detection can be achieved with the multispectral sensor during daytime conditions. This sensor system may also be useful towards early season yield estimation.

There is an effect of the phenological stage on the bud attachment strength which may have an indication about the timeliness for bud removal.

A concept of a pneumatic removal of excess buds was developed into a prototype field test system. In a first season, the highest achievable thinning rate was found to be 93.13 %, while in the second season this was only 74.52 %. This difference in performance was likely due to biennial bearing effects. Though these numbers were obtained during stationary field tests, they already give a good indication that pneumatic thinning is feasible and can be a viable alternative for the existing mechanized methods. It causes no damage to the bark and shoots, which reduces the risk of diseases spreading.

Based on the positive results achieved in this study, the test system can be further improved by use of more efficient nozzles, shorter duration of the air pulses and perhaps higher air pressure. Furthermore, experiments should be done with the nozzles operating while travelling along a fruit row, during which the distance between nozzle and bud is expected to vary. This will determine if the mechanism has to be able to precisely set the nozzle to bud distance. Overall bud removal during such tests can be easily evaluated based on the detection system. From these tests, it will then become possible to estimate the cost of pneumatic thinning in comparison to manual thinning. Furthermore, the effects on fruit quality, yield, return bloom and spread of disease should be investigated as well.

The position of the remaining buds and hence, the estimated position of fruits can also contribute to a more efficient use of tools in robotic harvesting.

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