Publication Information

Pub ID	Pub Date
11	2011 ASABE Annual Meeting Paper

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An ASABE Meeting Presentation

Paper Number: 11

Autonomous Mechanical Thinning Using Scanning LIDAR

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Written for presentation at the
2011 ASABE Annual International Meeting
Sponsored by ASABE
Gault House
Louisville, Kentucky
August 7 – 10, 2011

Abstract. *Hand thinning is a labor-intensive and expensive peach production practice. Mechanical thinning has been shown to be an economical method of reducing thinning cost. However, current mechanical thinning systems applied to perpendicular V systems require the operator to constantly steer the tractor to maintain engagement. This paper presents a system using a LIDAR to sense the canopy and automatically control the position of a modified Darwin string thinner position to maintain engagement. We demonstrate that the automated system is approximately as good as a human at maintaining canopy engagement by presenting blossom removal counts, and suggest that this may be an economically viable method of augmenting mechanical thinning.*

Keywords. Automation, Mechanical Thinning, LIDAR.

Introduction

Peaches and other fruit require thinning in the early growing season to produce marketable crops. It is generally accepted that thinning increases both overall yield and produces larger fruit (Miller et. al., 2011). Hand thinning is the current method widely employed but has the disadvantages of being labor intensive and expensive.

Figure 1. Before (left) and after (right) thinning Granny Smith apples at 80% bloom with the Darwin 300. The process removes about half the blossoms. From video captured by Craig Hornblow, New Zealand First. http://www.abe.psu.edu/SCRI/NZappleblossom.html

Mechanical thinning methods have been demonstrated to substantially decrease the labor required to perform thinning in crops where chemical thinning is unavailable or unviable (Schupp et. al., 2008). The Darwin vertical string thinner has been shown to be an economically viable method of performing nonselective mechanical thinning. However, the current method of applying the Darwin in perpendicular V systems requires the operator to weave in and out of the trees to maintain engagement with the canopy. Tractor operators report that this is physically and mentally tiring.

To address this problem, we have previously developed a system that uses hydraulic pistons to actuate both the angle and lateral position of the thinner (Dise, 2011). These pistons can be controlled with either a joystick or software. The operator drives in a straight line at a fixed distance to the trees and uses the joystick to maintain engagement with the canopy instead of weaving. However, this requires the vehicle operator to split her attention between the driving task and the thinning task.

We set out to fully automate the canopy engagement to reduce the operator load to operating the vehicle and monitoring performance. The weight and size of the thinner relative to the power of the hydraulics makes this problem somewhat difficult because the slow moving thinner cannot be moved instantaneously. Therefore the canopy sensor cannot be collocated with the thinner and must be placed ahead on the tractor body, where it maps the canopy as it passes. This allows the system to plan to maintain engagement while avoiding future collisions. These challenges are somewhat eased by the compliance of the system in both the strings and the trees: the long strings ensure that the positioning of the thinner does not need to be highly accurate, while the trees will bend in minor collisions.

We hoped to meet or exceed human performance at engaging the canopy for thinning while avoiding damaging the trees with the thinner. We measured our performance using both blossom counts and a comparison of the estimated percent of the canopy engaged by the operator.

Methods

Our experiments were conducted on peach (*Prunus persica*) trees in a perpendicular V system. This high-density system is conducive to automation but presents a challenge in mechanical thinning due to the varying shape of the canopy. With an unmodified Darwin thinner, the tractor must be steered in and out of the row to maintain engagement. An example of such a tractor path is shown in Figure 2.

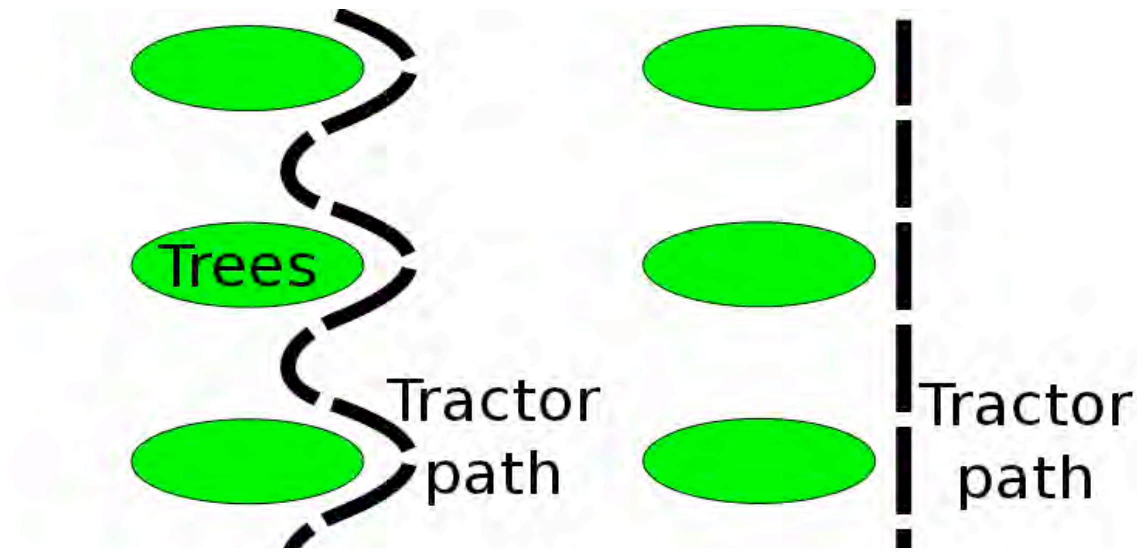

Figure 2. Diagram comparison of the tractor paths with an unmodified Darwin (left) and the actuated Darwin system (right) with both joystick and automatic controls. Note that the straight path is less burdensome on the operator, especially during long periods of thinning.

System

We used the previously developed hydraulic setup from Dise (2011). The system is a Darwin 300 mounted on the rear three-point hitch of the tractor with two major modifications to the Darwin thinner – an actuator and encoder pair that controls offset into the trees and another pair that controls angle of the thinner. The actuators provide 24 inches of lateral control along the leftward axis and 30 degrees of angular control about the forward axis, with an angular bias into the trees. See Figures 3 and 4 for a diagram and photograph. Encoders mounted to the actuators provide angle and lateral intrinsic sensing of the thinner position. A scanning LIDAR mounted near the front of the tractor maps the canopy as the tractor drives. All laser-based experiments in this paper use a Hokuyo Tough-URG, though we have mapped canopy in the past using a SICK LMS 111; several other environmentally-hardened LIDARs are also available. The LIDAR works by sending an infrared laser pulse out and measuring the time-of-flight to the trees and back. By spinning the laser and sensor, it is able to get distance measurements at 1 degree or better resolution sweeping 270 degrees. The distance measurements have subcentimeter accuracy, and full line scans are received at greater than 20Hz. There is a large body of work using laser range sensors to detect environment geometry in robotics, and more recently to sense tree geometry (Campoy, 2010) (Grocholsky, 2011) .

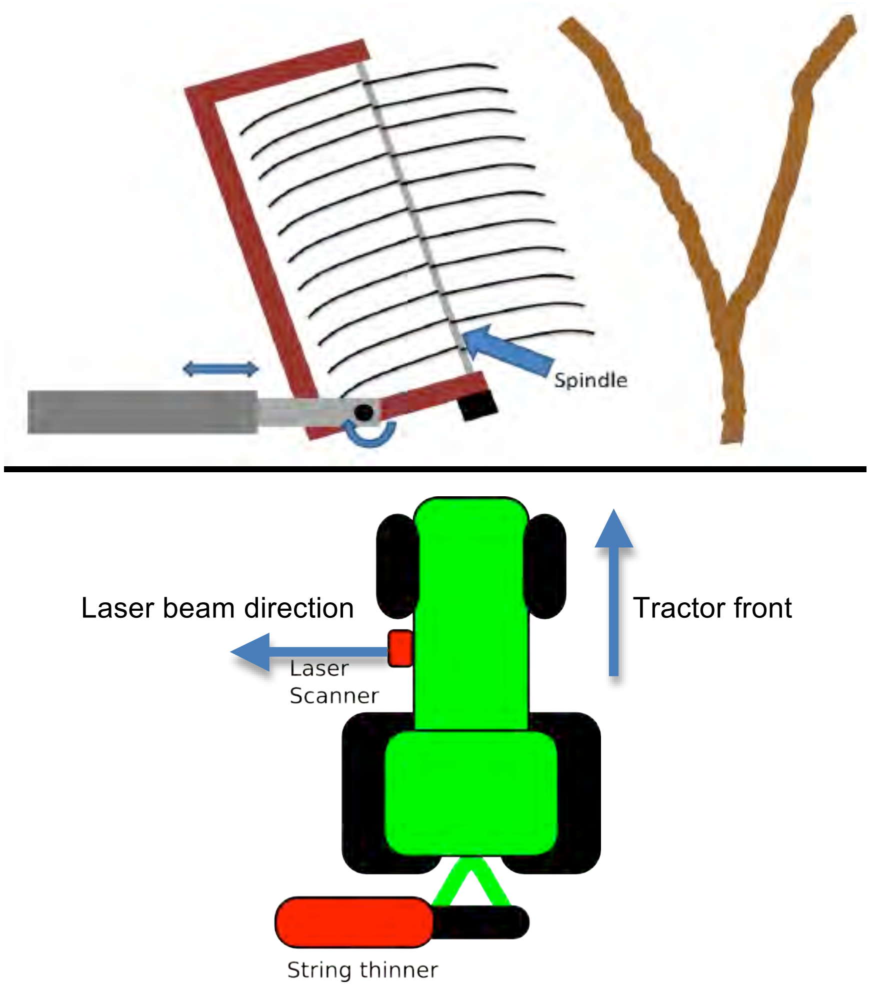

Figure 3. Top: a front view of the actuated thinner. Bottom: a top view showing the relative position of the sensor and thinner. The actuators have 24 inches of lateral range and 30 degrees of angle control.

The sensor is mounted ahead of the thinner so that the planning software can look ahead and plan and avoid future obstacles. Both sensor and thinner are mounted on the left-hand side of the tractor. To process the laser data, we divide the world into a 10 cm voxel grid along the leftward and upward axes of the tractor. For each laser return, the sensing algorithm counts the number of laser returns in each cell. Every 200 ms this two dimensional grid is stored as a sensor frame. Figure 5 shows an example of one such frame.

We address the planning task using an optimal control methodology. Figure 6 shows the dataflow through the control system. Each possible position of the thinner has a cost, representing lack of engagement with the canopy and collision with the trees. Let x be the current state of the thinner (given by its angle and lateral encoders) and z be the voxel grid built from the laser data. The cost of a particular state of the thinner given the voxel grid is:

$$Cost(x,z) = \sum_h engagement(thinnerEdge(x,h) + 0.1, canopyEdge(z,h))$$

where the summation is taken over each voxel row height *h* that contains the left edge of the thinner (given by the thinnerEdge function which calculates the thinner's edge position based on its reported lateral position and angle). The canopyEdge is the position of the rightmost occupied voxel in the grid at the height *h*. Both of these functions give values as leftward distances from the tractor – further corresponds to larger values. To reduce the chance of collision, 0.1 m is added to the calibrated thinner edge. Engagement cost is given by:

$$engagement(t,c) = \begin{cases} c - t & c - t > 0 \\ 10^6(t - c) & c - t \le 0 \end{cases}$$

The first case penalizes the thinner being far away from the canopy, while the second case penalizes collisions. Collisions are much more expensive than disengagement to decrease the likelihood of damage to the trees. The net effect is that the minimal cost will place the bar of the thinner 10 cm away from the edge of the tree, which should mean that 50 cm of string is engaged with the canopy.

To minimize the cost function and thus produce a desired trajectory for the thinner, we discretize both the world and the thinner actuators with respect to time. Due to the 5 Hz control loop on our hydraulics, groups of laser scans are binned into 200 ms chunks. For the actuators, we measured the time it takes for the hydraulics to move their full range -- in our case, 5 seconds for the lateral control and 4 seconds for the angular controller. Dividing these transit times by the control period of 200 ms gives us 25 and 20 cycles respectively to travel the range of the thinner. Therefore, we build a control grid with 26 by 21 states so that it is possible to move between any two adjacent states in one control cycle. We then assume the tractor is moving at a fixed speed to calculate the number of cycles between the current position of the thinner and the currently measured canopy. We also assume the rows are approximately straight to simplify the geometry.

Figure 4: Picture of the system used from side (left) and rear (right) views. Note the laser scanner in the bottom center of the side view (surrounded by red)– it scans in a plane parallel to the thinning plane.

By applying the cost function to each control grid cell once the measurement is complete for that cell, we are able to get the cost of occupying that state. We assemble these grids of state costs into a circular queue and calculate the optimal policy from the current state through all reachable future states up to the current measurement using value iteration. This is efficiently calculated by working backwards from the most recently sensed state to the currently actuated state and storing the cost of the optimal trajectory at each stage (Bellman, 1957). Up to discretization, this means that within our time horizon we fully solve the cost function and develop a cost-to-go, or value, function for each currently available state. The optimal current command is given by moving the thinner to the lowest cost-to-go neighbor state from the currently sensed thinner position.

Figure 5. An example voxel grid of a peach tree taken during thinning. Each green block represents an occupied 10 cm x 10 cm cell, meaning it had a laser return in it during the scanning period. The tractor is driving into the page and is on the right side of the tree shown.

At the planning stage, we also correct for the >300 ms of control lag in the system by reducing the number of future states available to plan within. The delay between the current laser sensor frame and the frame the actuator is in was set by hand given the tractor speed and the control lag to be 13 frames, which corresponds to 2.6 seconds. We also add in the obstacles from the two sensor frames just before the sensor frame currently occupied by the thinner; this penalizes colliding with objects just behind the thinner. These penalties are implemented as terminal cost -- the thinner is unable to plan for these states but takes the penalty of occupying them.

Our inner control loop takes the desired command and uses on-off control with a dead band of 6 encoder ticks to follow the trajectory. If the thinner is more than 6 encoder ticks away from the desired position on either axis, the actuator is commanded to go full speed towards the desired position. We chose this method due to the low performance of the hydraulic system relative to desired commands, and it works reasonably well in practice. A higher bandwidth inner controller would allow for smoother control that would take advantage of the proportional valves on the hydraulic system.

Experiment

We tested the laser-based control mode against a hand-controlled joystick mode in a research peach orchard. All tests were at 80% bloom during April of 2011 in Arendtsville, PA. We ran four test repetitions with each system, meaning we thinned four randomly selected halves of a row on a single side with each system. For each of these sections, we measured blossom counts at two heights from two pre-tagged test limbs in the center of each section and recorded laser and encoder data. Blossom counts were performed by hand before and after thinning. All trials were done at approximately 1.6 km/h tractor speed and the spindle rotation was 240 rpm.

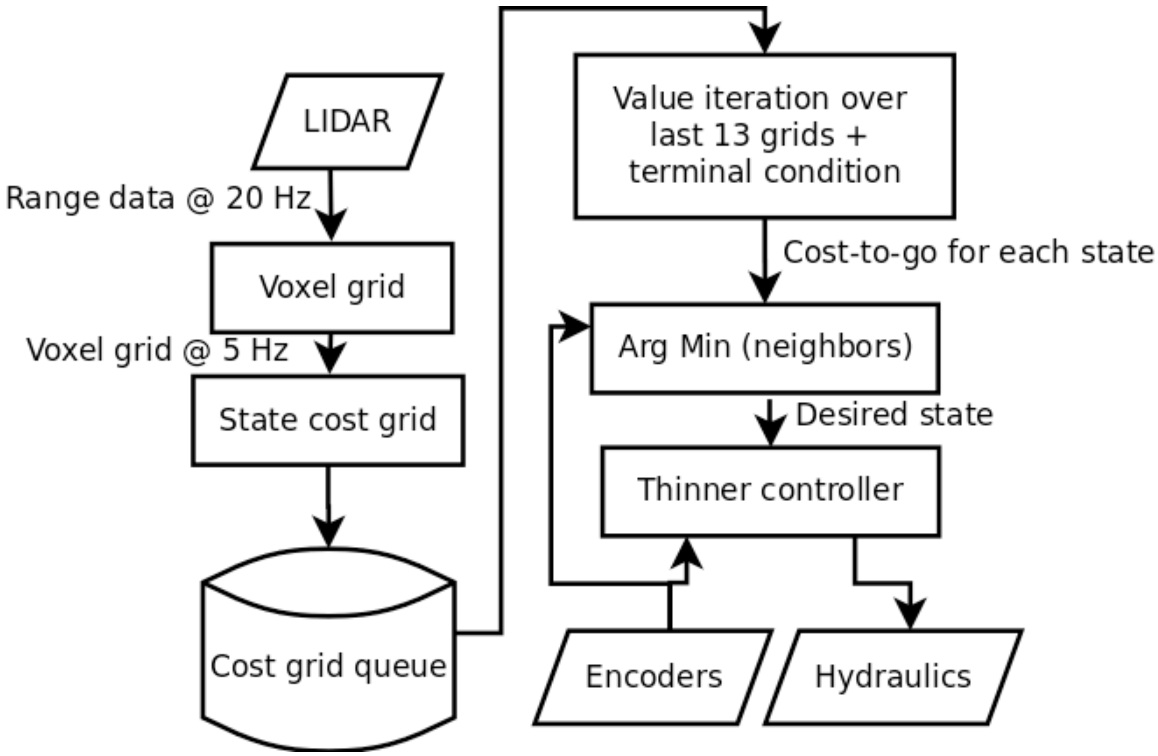

Figure 6. The data processing flow chart. The 13 grids are the tuning result based on the tractor speed and control lag to give us a time horizon of 2.6 seconds. Note that queue drops old cost grids once they are completely past the thinner. Value iteration with this time horizon compensates for the sensor being 2.7 meters ahead of the thinner.

Results

As shown in Table 2 in the appendix, we found that the laser control system performed similarly to the joystick control in blossom counts. Note that though the laser system was slightly less engaged on the lower canopy, the overall (scaffold) performance was much closer. Both the laser and joystick treatments over-thinned due to the combination of slow tractor speed and high spindle speed; the desired removal percentage in the table would be closer to 50%.

In addition to the biological results, we collected laser data and estimated the engagement of the trees during both trials. Our metric assumes the center of the trees are 2 meters from the center of the sensor and measures all occupied voxels between this mark and the sensor (omitting those occupied by the tractor – the laser does hit some tractor parts). We then use the encoder data to get the thinner position as it passed through these voxels and assume the strings are fully extended forming a cylinder around the spindle center. We use this data to count the occupied voxels engaged and missed by the thinner. We found that 68% of the voxels were engaged by the thinner during joystick mode while only 55% were engaged during the laser-based autonomy. The full results are shown in Table 1. Note that there is not enough data to make a statistically significant comparison, as this metric is very sensitive to driver behavior and the shape of the canopy. The laser-control algorithm is likely more conservative than the human operator as it is trying more aggressively to avoid collisions that the human operator would identify as being harmless, such as contact with small branches.

Table 1. Engagement percentage for each trial. 100% engagement would be desirable, but it would mean the thinner would collide with main branches, so the engagement percentage of the joystick operator is the nominal goal value.

Trial number	1	2	3	4	1	2	3	4
Method	Joystick	Joystick	Joystick	Joystick	Laser	Laser	Laser	Laser
Engagement percentage	71.55%	66.27%	65.13%	67.36%	52.99%	55.96%	45.88%	64.22%

The hydraulic system on the Deutz-Allis tractor is heavily taxed by the combination of the thinner spindle and the lateral and angular actuators. This causes unmodeled coupling between the two control axes, which will create problems when the desired thinner trajectory moves large distances in the control space. It created problems in spindle speed for both joystick and autonomous modes, with the spindle often going substantially slower than desired. Penalizing transitions would reduce but not fully solve this issue – a better solution would be a stiffer power supply, either by introducing addition hydraulic supply or changing the actuation technology.

Conclusions

We have shown that automated thinning is promising as a method for reducing operator load while successfully completing the task. Our biological results suggest that the laser-based control system performs very similarly to the joystick-based control system. The calculated voxel engagement results support this claim but with a larger difference than the biological results. Future work includes demonstrating that the automated system can quickly and reliably thin full blocks, and demonstrating in larger scale trials that operator fatigue is reduced over long periods. Any such trials would require improving the mechanical system to move the thinner quickly without affecting spindle speed and reducing the control latency to acceptable levels.

Acknowledgements

This work is supported by the USDA Specialty Crop Research Initiative program under grant no. 2008-51180-04876 and 2008-51180-19561. Thanks to Ben Grocholsky, Edwin Winzeler, and Robin Pritz for their support.

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Appendix

Table 1. Comparisons of flower removal and flower density in peach trees thinned with automated versus manually operated string thinner prototypes. Upper and lower canopy are the two height division of the trees, and scaffold is their combined count.

Thinning treatment	Blossom removal (%)[z]			Flower density after thinning (flowers/cm^2 limb-cross-sectional area)[y]			Blossom removal with variable accessibility[x] (%)	
	Upper canopy	Lower canopy	Scaffold	Upper canopy	Lower canopy	Scaffold	Scaffold with poor accessibility rating	Scaffold with good accessibility rating
Manually operated joystick	62.8 a	63.5 a	63.1 a	3.9 a	1.3 a	3.6 a	65.3 a	60.8 a
Laser controlled positioning	61.2 a	51.9 a	58.7 a	4.7 a	1.9 a	4.8 a	55.5 ab	61.8 a

[z] Determined from number of blossoms counted immediately before and immediately after mechanical thinning. All measurements are from one pre-tagged limb from each of two center trees per replicate.

[y] 1 flower or fruit/cm^2 = 6.4516 flowers or fruit/inch^2.

[x] Scaffolds with good accessibility (5 on a 1 to 5 scale) straight and oriented at 65 degrees from horizontal; scaffolds with poor accessibility (1 on a 1 to 5 scale) were curving with multiple angles.

[w] Tractor speed was 1.6 km·h^{-1} , spindle rpm was 240. Treatments were applied at 80% full bloom.

[v] Mean separation within columns by Fisher's protected least significant difference at $P \leq 0.05$.