Diameter sensors for tree-length harvesting systems

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Summary

Most cut-to-length (CTL) harvesters provide sensors for measuring diameter of trees as they are cut and processed. Among other uses, this capability provides a data collection tool for marketing of logs in real time. Logs can be sorted and stacked based on up-to-date market information, then transportation systems optimized to route wood to proper destinations at lowest cost. This capability does not currently exist in tree-length logging systems common in the US South, but that deficiency may soon have to change as wood and fibre companies in the region adopt technology in order to reduce delivered wood costs. CTL logging systems may become more common in the region as this change occurs, but tree-length will remain an important mode of harvest for many years. In order to take advantage of logistical technology to lower costs, as well as other potential benefits of 'precision forestry', tree diameter sensor systems for feller-buncher-type harvesting equipment will be needed. This paper presents some preliminary results comparing the performance of two alternative approaches to measuring tree diameter as a tree is being cut using a feller-buncher equipped with a rotating disk saw. One approach used a set of lasers to time the passage of a tree through the saw blade and into the head, then inferred diameter from this information. The other system resembled a class of yield monitors used on cereal grain combines, measuring the mass of chips being ejected from the saw head as an indicator of tree diameter. Both systems were implemented in a laboratory setting, with the laser system further deployed and tested on a feller-buncher. Both systems showed potential, with the laser device having advantages in apparent accuracy and survivability in harsh operating conditions.

***Keywords**: precision forestry, yield monitor*

Introduction

Logistical technology recently introduced into the forest products industry has changed the way in which standing timber is valued. Without logistical support, timber is treated as a commodity that flows into a conversion facility with the expectation that it fits the needs for the product being made. Marketing of timber is based primarily on delivered price, rather than total return to the conversion facility. This separation of the procurement and manufacturing can lead to much wasted effort and energy in such a system if purchased wood is not entirely suitable for the product it is to become.

Application of logistics in the marketplace means that information about quality of timber is available at the time of purchase. Decisions to procure timber can then be based on standards that ensure optimal use of the raw material, increasing returns and reducing waste. Although this approach is taking hold in many parts of the world, it has not been widely adopted in the southern US. In that region, there is little incentive to market wood to specific customers based on quality. One barrier to adopting a more technologically based market system is the type of harvesting systems employed. Nearly all of the wood produced in the southern US is harvested and transported tree-length. Tree-length logging systems typically do not use the sensor technology available on cut-to-length (CTL) equipment. Without these tree size and quality sensors, there is no data available to drive a tree marketing system and wood continues to be sold on a tract basis.

This study was initiated to investigate methods of sensing diameter of trees harvested in a tree-length logging system. The intention was to sample diameter at the point the tree was cut. This approach would not only fulfil the need for a stem marketing system, but would also serve as a *de facto* yield monitor. Mapping of yield in agricultural crops has become commonplace. A farmer evaluates variations in yield in order to design site-specific prescriptions to maximize growth potential and reduce amount of herbicide and fertilizer inputs. The same approach may prove useful in forestry, but it will not be possible to evaluate the potential of this 'precision forestry' management approach without a yield monitor system.

The objective of the study was to evaluate two potential sensing technologies that might be useful for measuring diameter of trees as they were cut using feller-bunchers. One sensor used an optical approach to measure tree diameter, the other sensed impact forces from the waste stream of a felling saw as an indicator of diameter. Both sensors were built and tested under laboratory conditions. The optical sensor underwent limited testing in field conditions.

Experimental Procedures

Tree-length harvesting equipment is designed to operate in very difficult conditions, and sensors designed to work in feller-bunchers must be chosen with those conditions in mind. Felling heads typically used on a feller-buncher are not designed to grab individual stems, meaning that the primary sensing element used to measure diameter must be of a non-contact variety. Ideally, a diameter sensor would be mounted out of the way of limbs and other hazards and not require extensive modifications to install. These limitations suggested the use of proven technology that could be 'hardened' to withstand the rigors of the woods environment. Optical and force-sensing systems were chosen for evaluation.

Previous success applying lasers in mass flow measurement of granular materials (Grift et.al., 2001) led us to believe that the same principle could be applied in measuring tree diameters. Laser sensors would be simple to implement and would not require any significant modifications to the carrier machine to mount. On the negative side, however, the sensors would have to be mounted at the throat of the saw head, exposed to quite a few hazards. Depending on the height of the sensor above the ground, it could be subjected to interference from dirt, flying debris, or limbs.

Impact force sensors are quite accurate in measuring grain yields in combines (Reynes et.al., 2002). Grain is thrown off the combine's conveyance system against a force transducer. Measured force of the impact is proportional to the change in momentum that the grain kernels undergo, and if the velocity at which the grain is thrown against the transducer is relatively constant and the impact is elastic, the momentum change will essentially be a function of the mass of the kernels. A similar situation is found in feller-bunchers. As a tree is severed from the stump, the material from the saw kerf is ejected out of the side of the felling head. The mass of this stream of chips should be related to the size of the tree, and if a force transducer could be mounted in a fashion to deflect the stream, this information could be used to measure tree size.

Optical Sensor

Using timing signals generated from the interruption of two laser beams to measure size of an object is very straightforward provided the velocity of the object remains constant while travelling across the beams. For that case, the timing signals might appear like that shown in Figure 1, and the diameter can be calculated from the equation

$$D = b\frac{t_1}{t_f} \quad . \qquad [1]$$

It is unlikely, however, that trees entering a saw head, particularly if they were large, would be travelling at a uniform velocity. If the assumption is made that the rate of change in forward velocity while a tree is severed is constant, then the diameter can be calculated using

$$D = t_1\left(\frac{b}{t_f} + \frac{1}{2}a(t_1 - t_f)\right), \qquad [2]$$

where a is the (constant) deceleration rate. The parameter a can be estimated using the relation

$$a = 2b\frac{(t_f - t_e)}{t_f t_e (t_1 + t_2)} \quad . \qquad [3]$$

The sensor constructed for this study used a set of 4 lasers (Opcom Model No. OLUX305P) in sequence, giving the ability to make 3 independent estimates of the tree diameter for each pass through the saw head. The lasers were housed in an aluminium case and mounted in self-aligning bearings that provided a degree of motion to aim the laser. Once aimed properly, the direction of the lasers could be fixed using setscrews in the top of the housing. The detector side of the sensor consisted of 4 photodarlington transistors mounted behind 25-mm diameter optical lenses with a 25 mm focal length (Edmunds Scientific NT45-364). As long as a laser beam hit some point on the lens, the sensor was energized. This arrangement compensated for movement of the beams because of machine vibration.

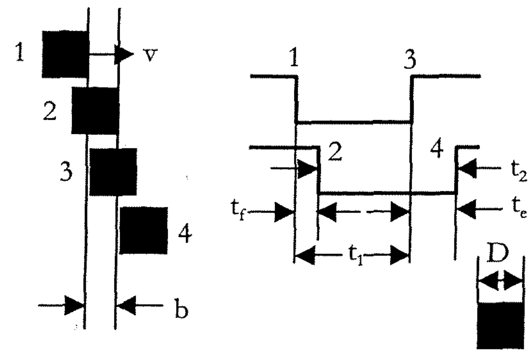

Figure 1. Illustration of the timing signals measured using the laser diameter sensor. The vertical lines on the left are the laser beams, separated by a distance b. *An object of diameter* D *is passing through the beams at velocity* v *and the output of a detector indicating passage of the beams is shown in the upper right. Transition points (when the detector states change) are labelled* 1, 2, 3, *and* 4.

Output of the optical sensors was fed through a comparator that switched states when light from the lasers was blocked. The output of the four comparators (one for each laser) served as input to a logic circuit that combined the independent signals into one. The logic output changed state whenever an on-off transition was observed from any of the optical sensors. A plot of a typical output from the logic circuit is shown in Figure 2. This pattern was characteristic for objects with diameters larger than the total distance between the first and last lasers (100 mm).

Impact Force Sensor

It was thought to be impractical to modify an existing feller-buncher to measure impact forces from ejected saw waste without some certainty that the method would be accurate enough to justify the expense. A test apparatus was therefore constructed to simulate the stream of chips in a laboratory setting. The exit velocity of chips from a feller-buncher saw head was estimated to be possibly in excess of 90 m/s. If 1 kg of chips were to be thrown at that velocity over a period of 1 s, the power requirement would be about 9 kW. That number could easily rise to 15 kW when losses were considered. A pneumatic launch device was deemed the simplest and cheapest means of achieving that level of power input safely in a test apparatus, with the added benefit that there was considerable practical experience in building such devices available locally for consultation (Veal et.al. in press). The launch device as used in these tests was very similar to pneumatic cannons built for other projects. Construction was entirely of PVC pipe and fittings. A 25 cm wide by 3 m long section of pipe was used for the main reservoir, with a 10 cm wide by 4.3 m long barrel. Design pressure to achieve an acceptable launch velocity was estimated be about 2 bar.

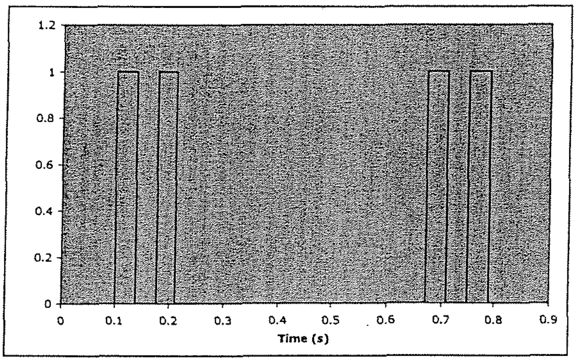

Figure 2. Typical output of the logic circuitry when an object wider than 100 mm (in this case a tree) passed through the laser sensor. The logic '1' state corresponded to a circuit output of 5 volts. The state changes on the left of the figure corresponded to a laser becoming blocked, while those on the right were the lasers becoming unblocked.

The chips were shot into a PVC 90°-elbow section that was 15 cm in diameter. A 9-cm square section of the elbow was cut out at a point about half way through the elbow. A piezoelectric force transducer (Omega Engineering DLC101-500) was attached to the removed plate, which was then remounted into position in the elbow with additional structure such that the plate occupied the place from which it was removed. Further mounting structure was constructed so that as chips exited the cannon they entered the elbow and were redirected downward into a receptacle. The force required to effect this change in momentum was measured using the transducer.

The transducer produced a voltage signal that was proportional to force. This signal was recorded using a digital-to-analog converter (Capital Equipment Corp WEBDaq 100) at a rate of 40 kHz. A plot of force as a function of time typical of the test conditions is shown in Figure 3.

Experimental Tests

Initial optical sensor tests were conducted with the lasers mounted on a feller-buncher. Results were not successful primarily because of debris thrown from the saw head clogging the aperture through which the lasers were directed. Further limited tests were conducted with the transducer mounted on the fork tines of a skid-steer loader, eliminating the need to worry about flying debris. The sensor was used to measure the diameter of a vertical PVC pipe, and the DBH of several pine trees. There were again complicating factors that limited the performance of the sensor, this time the problem of ambient light causing false state changes in the output logic circuit. Because of these problems, results were obtained for only the pipe and one tree.

The impact force sensor was tested using clean chips to simulate saw waste. Tests were conducted with two levels of chip mass (1 and 0.5 kg) and two reservoir initial pressures (1.7 and 2.1 bar), with five replicates made for each treatment.

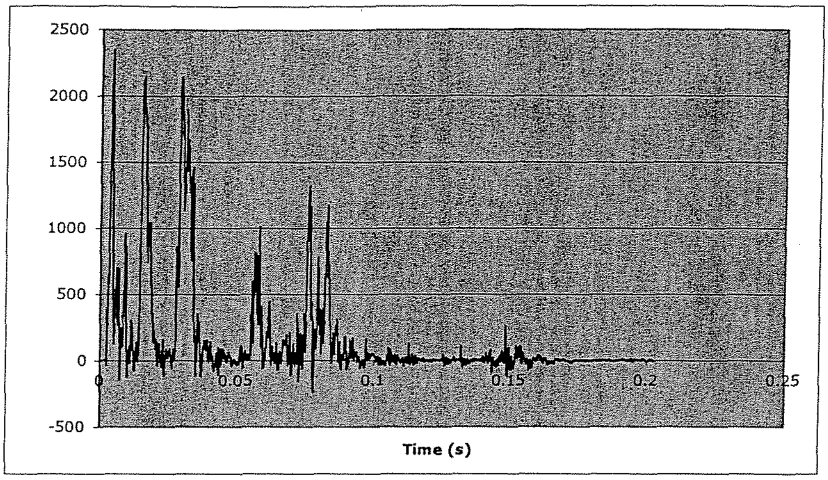

Figure 3. Impact force recorded for a 1.0 kg sample of chips shot from the pneumatic launcher at 1.7 bar.

Results and Discussion

Optical Sensor

Interference from sunlight was a major, unexpected problem with the optical diameter sensor. The interference, when present, made it impossible to associate a specific transition in the circuit output to the object blocking or unblocking the laser beam. The cause of the problem is unknown, and attempts to eliminate it have so far been unsuccessful. When the object was not in direct sunlight, however, it was sometimes possible to get a valid sensor output. The rate of success was low even under these circumstances, but estimates were obtained for a PVC pipe and for one pine tree.

Results from the pipe were used to calibrate the sensor. The lenses on the detector portion of the sensor compensated for small vibrations that might have caused temporary misalignment of the beams. If, however, the beam were not perfectly perpendicular to the detector plane, the detector would still see the beam but diameter measurements would be biased. This bias was corrected for using an object of known diameter, in this case a section of pipe, to calibrate the distance between the detectors (*b* in equation [1]). The nominal distance was 33 mm, but beam variance would show up as this value changing across the laser pairs. Two separate measurements of the pipe diameter produced valid data, and the average of the measurements of laser separations were found to be 33.4, 35.1, and 29.8 mm.

These separation values were used in calculating diameter of the pine tree for which valid data were obtained. Two passes were made, giving a total of 6 estimates of tree diameter. Results are summarized in Table 1. The overall mean estimated diameter was 50.8 cm. Measured dbh of the tree was 51.9 cm, a difference of 2 percent. Standard deviation of the estimates was 1.5 cm, or 3 percent of the mean value. Estimated mean diameters for the two passes were 51.3 and 50.3 cm, a difference of 2 percent. No effect of change in velocity was observed in these tests, so the correction of equation [2] was not applied in calculating diameters.

Table 1.
Diameter of a single pine tree estimated using the laser sensor. Values reflect two passes made using the sensor, with three estimates made on each pass. Actual diameter of the tree was 51.9 cm.

Pass	Sensor Position	Diameter Estimate (cm)
	1	49.4
1	2	52.5
	3	52.1
	1	48.8
2	2	51.8
	3	50.3
Average		50.8
Standard Deviation		1.54

In this single instance, the performance of the optical sensor in measuring the tree diameter was quite good. It would be optimistic to assume that errors observed in these limited tests would be indicative of those for a working sensor, but even if error rates were double those observed here, the sensor would be acceptably accurate. Several problems must be overcome to realize a working model of this sensor, primarily the debilitating effect of ambient light. These results are encouraging, however, and continued development is being pursued.

Impact Sensor

Peak impact forces observed from the tests were quite large, over 2000 N for each treatment. This result emphasized the difficulty in creating a working model of this type of sensor. Even with a relatively low density, wood chips shot at a high velocity create large impact forces. Materials coming out of a disk-type saw head could potentially be of much greater density, meaning that any impact force sensor will have to be extremely rugged to survive.

Velocities of the wood chips were estimated using an infrared timing gate sensor. Two infrared LEDs emitted a signal that was sensed using two detectors. A digital oscilloscope was used to time the progress of the chips leaving the cannon. The sensor did not provide a definitive velocity estimate because of the particulate nature of the chips – it was difficult to match timing events across the detector to specific chips, or clumps of chips. Using a great deal of judgement in interpreting the results, it was estimated that exit velocity of the chip stream was well below the theoretical value of nearly 100 m/s at 2.1 bar reservoir pressure. The measured values were about 1/5th of this velocity, perhaps because of the relatively high frictional losses from the chips rubbing on the barrel walls as they were pushed out. Despite the relatively low exit velocities, measured forces were quite high.

Two sets of measures were calculated from the force data, the first being simply the average of measured values over the entire sampling window. For these tests, that amounted to just over 200 ms of data. Mean force values are summarized in Table 2. An analysis of variance showed that chip mass was significantly related to mean force ($P < 0.001$), but that reservoir pressure was not. Reservoir pressure was the primary factor influencing exit velocity of the chips, and the fact that it was uncorrelated to mean force indicated that, at least for small variations, the impact sensor could be insensitive to velocity changes. It is unlikely that this result would hold true for velocity changes of any significance, but it does indicate that small changes, for example that might result from tooth wear on the disk saw, might not affect accuracy.

Table 2. Mean and (standard deviation) of force over the entire impact as a function of launcher reservoir pressure and total chip mass. Units are in N.

Chip Mass (kg)	Reservoir Pressure (bar)	
	1.7	2.1
1.0	140 (18.2)	144 (4.00)
0.5	62.6 (4.88)	76.4 (17.6)

The power spectra of the force data were also calculated and values at various frequencies were tested for their ability to predict mass of chips. Figure 3 shows spectral density estimates for the frequency range of 0 – 25 Hz. Mass clearly had the greatest influence on spectral density over this frequency range, with pressure showing an effect for the 0.5 kg mass level. Table 3 summarizes results from an analysis of variance that modelled power spectral density as a function of mass and pressure at 5 Hz frequency intervals. Chip mass was significant at all frequency levels in predicting spectral values ($P < 0.001$), except at 0 Hz. This was surprising since the 0 Hz power spectral density term represents the mean of the force response, which is normally considered to correlate most strongly with impact force (Savoie et.al., 2002). In this study, the strongest relationships between spectral values and mass were observed at higher frequencies. Pressure was not a significant correlate of spectral density at the lower frequency values. It was, however, significant at 15 and 20 Hz, perhaps because of a resonance effect of the impact on the sensor mounting structure.

Conclusions

There was a clear relationship demonstrated between mass of chips launched in a stream at relatively high speed and various measures of the impact force. Although this was encouraging, it was not considered definitive evidence that this type of sensor would perform with sufficient accuracy to be of use as a tree size sensor in a working environment. Accuracy of the sensor has not been established given the additional variability that is likely to be found when mounted on a machine. The survivability of such a sensor under such harsh conditions would also be questionable. If it could be built to last and was accurate enough to measure mass of chips ejected from the saw head with precision, the relationship between that mass and tree size would add additional variability.

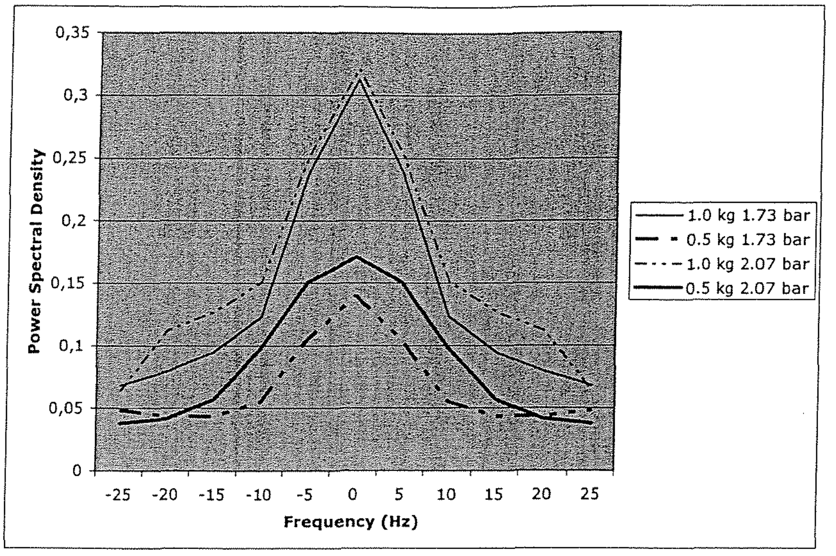

Figure 4. Power spectral density estimates of the force data. Power spectrum values are in units of volts – to convert to N multiply by 444. The estimates were based on smoothing of the five replicates for each mass-pressure treatment.

Table 3. Significance (P) values for the ANOVA model fit to the power spectral density data, by frequency. Values in the R^2 column indicate the model coefficient of determination for that frequency.

Frequency (Hz)	Mass	Pressure	R^2
0	0.301	0.555	0.08
5	0.005	0.812	0.38
10	0.002	0.272	0.41
15	0.001	0.019	0.58
20	0.001	0.006	0.91
25	0.001	0.232	0.89

The optical sensor was found to be accurate, although its practical feasibility has not been proven because of the operational problems encountered with ambient light. Given that this issue can be overcome, perhaps through the use of infrared, rather than visible light, lasers, the issue of survivability will have to be addressed. A mounting system that protects the sensor without interfering with operation of the feller will have to be devised. Given that can be done, the measurements should be accurate enough for estimating tree size to within 10 percent, provided the effects of velocity change can be compensated for.

Either sensor system could likely be made to work in practice to estimate tree diameter. The most significant drawback in both cases, however, is that they provide only a single estimate of diameter for a tree. This single estimator of tree size might not be accurate enough to provide information useful in managing stands, harvesting operations, or wood marketing.

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