Computer Vision for Grading Tree Seedlings'

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A computer vision algorithm measuring several morphological characteristics of pine seedlings was developed. Singulated seedlings were inspected on a moving belt at production-line rates. Classification as acceptable or cull was based on minimum criteria for stem diameter, shoot height, and projected root area. Individual seedlings were graded in approximately 0.25 seconds. Average classification error rate was 5.7 percent.

INTRODUCTION

Hundreds of millions of tree seedlings are grown annually in commercial, federal, and state nurseries. At harvest, these seedlings are graded to remove inferior stock and improve productive potential. Advances in equipment and cultural practices leave seedling grading as the only remaining labor-intensive operation at most nurseries.

Grading is typically performed manually through application of a number of visual quality criteria. Although stock types and cultural practices vary widely among nurseries, several generalizations may be made about current grading practice. Manual inspection tends to be labor-intensive and costly. Seedling classification is subjective and susceptible to human error. Grading and sorting into multiple acceptable classes is not feasible. Valuable production data, including morphological statistics and cull rate, are difficult to obtain. Disadvantages of manual grading have spurred growing interest in automated alternatives.

Automated systems have been constructed for measurement of seedling characteristics (Buckley et al., 1978) and seedling grading (Lawyer, 1981). Mechanical and opto-electronic methods were used to successfully measure stem diameter, shoot height, and projected root area, however, neither machine could match manual grading productivity.

Digital image processing has been successfully implemented in many industrial and agricultural inspection processes. It has demonstrated high accuracy and throughput, permitting 100% inspection where product sampling was previously the only feasible method of quality control (Kranzler 1985). Machine vision inspection would appear to be an ideal tool for addressing the tree seedling grading problem.

OBJECTIVES

This study was initiated to investigate the ability of machine vision to grade bare-root pine seedlings under nursery production conditions. Specific objectives included:

1. Develop and implement a machine vision algorithm to measure key morphological characteristics and grade seedlings at production-line rates.
2. Evaluate performance in terms of measurement speed, precision, and accuracy of classification.

METHODS AND MATERIALS

Assumptions

Several assumptions were adopted concerning the environment in which commercial grading would be performed. First, seedlings would be singulated, permitting only one seedling to appear within the camera Meld-of-view at a given time. This requirement could be relaxed to the constraint that adjacent seedlings simply must not touch. Singulation is straightforward for container-grown seedlings, but bare-root stock requires special handling equipment (Graham and Rohrbach, 1983).

Second, loose constraint of shoot orientation (+/30 degrees) and lateral position (+/- 6 cm) was imposed. Orientation and position constraints simplify both hardware and software, but are not necessary for

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commercial implementation. Finally, it was assumed that a black conveyor belt would be used to transport seedlings beneath the cameras. Again, other configurations are possible, for example, acquiring images as the seedlings fall past a backlight.

Equipment

Equipment included a conveyor belt, machine vision computer, cameras, lenses, and lights. To simulate production grading operations, a variable-speed belt conveyor was constructed to transport seedlings for inspection. The shiny surface of the black belt was dulled by sanding to minimize specular reflection.

An International Robomation/Intelligence (IRI) D256 machine vision development system was used. Images were digitized into an array of 256 X 240 picture elements (pixels) with 256 grey levels of intensity. A high-speed hardware coprocessor performed computationally intensive operations such as image windowing, filtering and edge detection, run-length encoding, and moments calculations. Software was developed in the C programming language.

Two Hitachi KP-120U solid-state black-and-white television cameras were employed for image acquisition. Camera 1 was used to obtain a close-up image of the seedling root collar zone. A field-of-view (FOV) approximately 12.8 cm (5 in) square provided a 0.5 mm (0.02 in) pixel resolution (fig.1). Camera 2, with a FOV approximately 51 cm (20 in) square and resolution of 2.2 mm, acquired an image of the entire seedling.

Illumination was provided by fluorescent room lighting and strobed xenon flash. Relatively low-level room lighting was adequate for detection of the moving seedlings in the FOV of camera 2. When a seedling was detected, synchronized strobe lamps were triggered to obtain a "frozen" image with each camera.

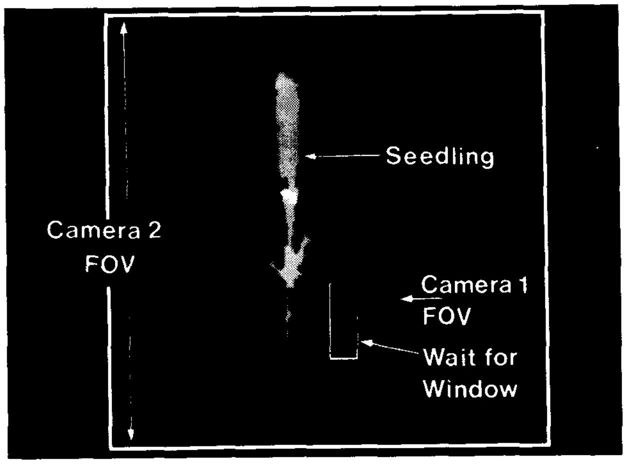

Figure 1.--Field-of-view for cameras 1 and 2. Note Waitfor window.

Grading Scheme

Morphological characteristics are used for grading most nursery stock. These characteristics include stem diameter at the root collar, shoot height and weight, root weight or volume, root fibrosity, foliage color, presence of terminal buds, shoot/root volume ratio, and ratio of top height to stem diameter (sturdiness ratio) (Forward 1982, May et al. 1982). Stem diameter, shoot height, and root volume are generally given priority and were adopted as the grading criteria for this study. Of these three, stem diameter is typically considered most important.

To meet image processing time constraints, we decided to emphasize stem diameter measurement accuracy and obtain close approximations of shoot height and of root volume as indicated by projected root area (root area index). A classification scheme based on minimum acceptable values of these three parameters (May et al. 1982) is given in table 1. Seedlings were graded into two classes; acceptable and cull.

ALGORITHM

The grading algorithm is composed of several separate tasks. These are: calibration, seedling detection, shoot orientation measurement, root collar location, diameter measurement, root area measurement, shoot height measurement, grade classification, and recording of seedling statistics. A detailed description of the algorithm is presented by Rigney (1986).

Selection of FOV for camera 1 required a compromise between diameter measurement precision and the probability of the root collar appearing within the FOV. Because the lateral position of the root collar cannot be tightly constrained, a relatively wide FOV is necessary. We decided to make the FOV as large as possible, while maintaining a measurement precision of at least 0.5 mm (0.02 in). Selecting 0.5 mm as the pixel resolution yields a 12.8 cm FOV. Measurement precision can be increased through use of a smaller FOV and more precise seedling handling or by substituting a higher resolution camera/computer system.

Seedling Detection

Under ambient lighting conditions, a sequence of images acquired with camera 2 (wide FOV) is processed as follows. Each image is masked by a template defining a window in which seedling presence is tested (Waitfor window, fig. 1). Seedling detection triggers image acquisition from each camera with strobe illumination. In the following algorithm descriptions, image 1 and image 2 refer to images acquired by camera 1 and camera 2, respectively.

Seedling Orientation

Image 2 is first processed to determine seedling orientation on the conveyor belt. Area moment calculations provide the angle between the seedling major axis and the vertical axis of figure 1.

Table 1.--Grading scheme for loblolly pine seedlings

Stem Diameter (mm)	Root Area Index (pixels)	Shoot Height (cm)	Grade
3.0 to 8.0	> 200	> 16	Acceptable
Otherwise			Cull

Subsequent measurements of stem diameter and shoot height are corrected for orientation angle. Because measurement error becomes excessive at large angles, seedlings are not graded if the orientation angle is greater than thirty degrees.

Location of the Root Collar

Accurate location of the root collar is crucial for subsequent measurement of stem diameter, shoot height, and root area index. Image 1 (small FOV) is processed by an iterative algorithm to find a collar location satisfying heuristic criteria. Consider each horizontal line in the image to be composed of pixel strings belonging either to the foreground (seedling) or background (conveyor). Further, define the frequency of a line to be the number of transitions between the foreground and background. The root collar may intuitively be expected to be located in a region of low frequency lines bounded by areas of higher frequency. Needles, branches, and roots contribute many transitions to horizontal lines in figures 2 and 3 (high frequency). Lines in the root collar zone contain significantly fewer transitions. The width of individual pixel strings is also exploited, since we have a priori knowledge of the expected stem width.

Line frequencies are processed to build a list of root collar candidates. The resulting list is processed to locate the root collar both vertically and horizontally. The algorithm will find the root collar of most seedlings in one iteration. Seedlings with branches, needles, or roots in the root collar zone require two iterations for collar location.

The scale and mapping relationship between images 1, and 2 was previously determined during system calibration. After locating the root collar in the close-up image 1 the collar location is mapped into image 2.

Measurement of Stem Diameter

Diameter measurement processing is performed inside a region around the root collar location in image 1. Region size is defined by the set of candidate collar lines found in the collar location subroutine. The region is processed with an edge detector favoring vertical edges, since we know that shoot orientation is approximately vertical. An edge detection operation yields an image of edge intensity. The average distance between the strongest edges bracketing the root collar is calculated as the collar diameter (fig. 4).

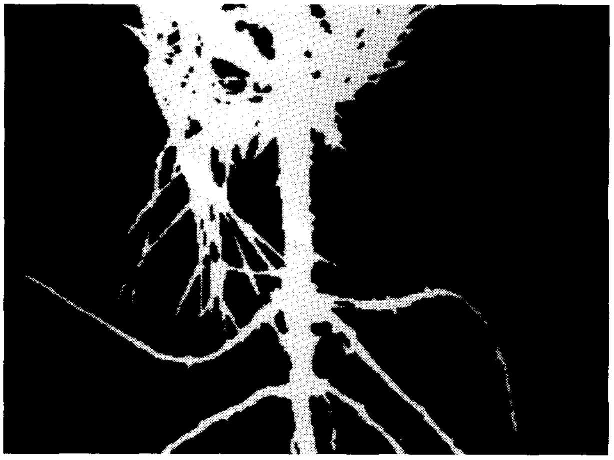

Figure 2.--Camera 1 close-up image details root collar region.

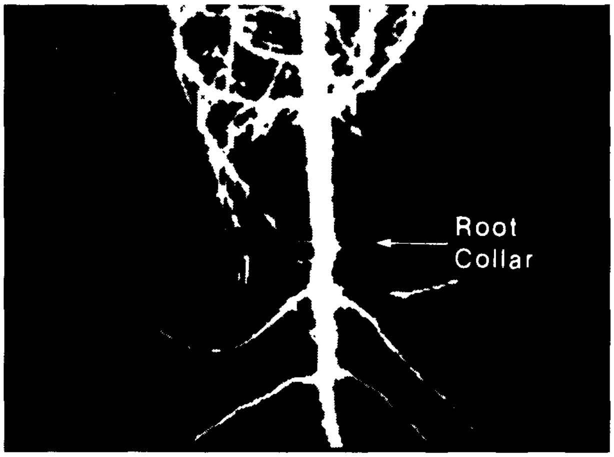

Figure 3.--Algorithm locates root collar.

Measurement of Root Area Index

Root area index is measured from that portion of image 2 below the root collar (as mapped from image 1). An edge detector sensitive to all edge orientations is applied. The weakest edges detected are the result of noise in the image background (conveyor belt). Above the noise level, however, roots much smaller than the pixel dimension (2.2 mm) can be detected because of their contribution to the brightness of a corresponding pixel. Pixels with edge intensities greater than the noise level are summed to yield projected root area (fig. 5).

Measurement of Shoot Height

Image 2 is processed to determine shoot height. Starting at the top of the image, each line is tested to determine if it has enough information to indicate the presence of the seedling top. The seedling top is assumed to be located when four consecutive lines meet this criterion. Shoot height is defined as the distance between the seedling top and root collar (previously mapped into image 2).

Measurement of Shoot Area

Projected shoot area is determined from that portion of image 2 above the root collar. Pixels with an intensity greater than the background intensity are counted to provide area. This measurement was amended to those described above to allow calculation of shoot/root area ratio.

Main Program

Inside the main program loop, values returned by subroutines are tested to control program flow. If all grading subroutines are successful in their respective tasks, a grade classification is assigned to the seedling.

Whenever a subroutine fails its task, the seedling is recorded as not gradable. Finally, measured seedling parameters, grade, and count are written to a statistics file.

Calibration

Proper calibration of threshold values and scale factors is essential for optimum algorithm performance. The calibration subroutine initializes sixteen parameters with default values. The user is then provided an opportunity to interactively alter the default values. A wooden dowel of known diameter and length is used to calibrate scale factors. Grey level thresholds are set using a representative seedling. Algorithm performance was relatively insensitive to grey level thresholds if "reasonable" values were selected. Threshold selection could be automated in a commercial implementation, eliminating operator subjectivity.

EVALUATION

A reference set of 100 loblolly pine (Pines tacda L.) seedlings was manually measured and graded. Stem diameters ranged from 2.3 to 6.0 mm. Performance of the machine vision system was then evaluated by grading each of the seedlings twenty times. Shoot orientation was limited to plus-or-minus thirty degrees from vertical, and root collar location was constrained to the FOV of camera 1.

Time required for the algorithm to grade a seedling averaged approximately 0.25 seconds. Strobe illumination provided reliable image capture at conveyor speeds of up to 1.0 m/s (3.3 ft/s), corresponding to a grading rate exceeding three seedlings per second. To facilitate manual placement of the seedlings on the conveyor, tests were conducted at a belt velocity of 0.5 m/s (1.5 ft/s).

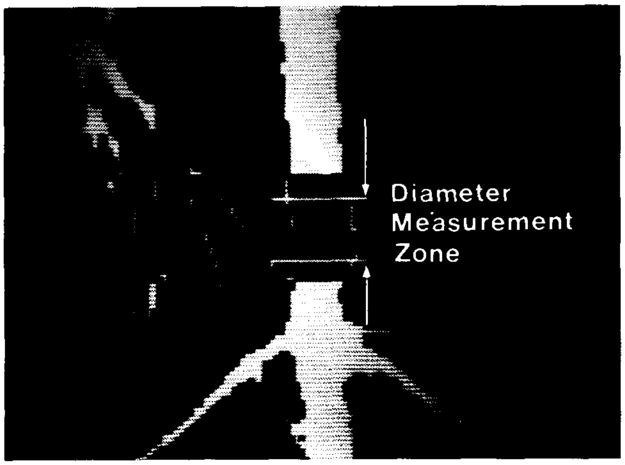

Figure 4.--Image is processed to define stem edges in root collar zone.

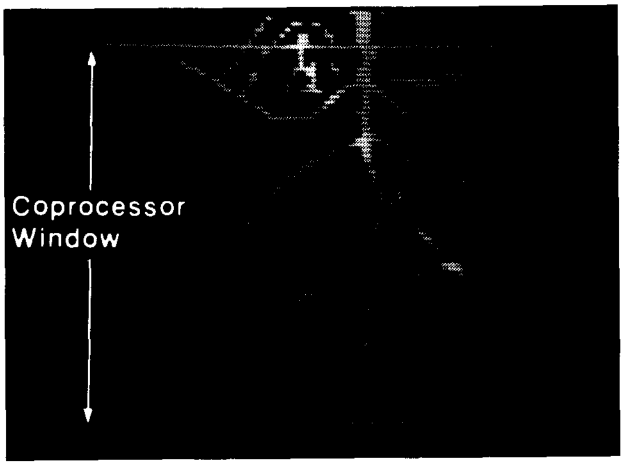

Figure 5.--Image is processed to highlight seedling roots.

Table 2.--Percent misclassification of 100 seedlings, 20 reps

Manual Grade	Acceptable		Cull		Total		
	#	mis.	#	mis.	#	mis.	n.g.
Borderline	6	31.7%	11	18.6%	17	23.2%	2.6%
Easily Classified	63	2.2%	20	2.0%	83	2.2%	2.3%
All	69	4.7%	31	7.9%	100	5.7%	2.3%

n.g. = not gradable mis. = misclassified

The classification error rate averaged 5.7 percent for the set of 100 seedlings (table 2). This is very acceptable performance, bettering manual grading operations which have an average misclassification rate of seven to ten percent (Boeckman, 1986). As expected, a large part of the classification error was attributable to seedlings which straddled the borderline between acceptable and cull, with respect to diameter and root area. Such seedlings comprised 17 percent of the grading test set and had an average misclassification rate of 23.2 percent. The remaining 83 seedlings had an average misclassification rate of 2.2 percent (table 2). Since there is no significant penalty for misclassification of borderline seedlings, 2.2 percent misclassification may be a better indicator of algorithm performance.

Measurement precision was excellent, considering the spatial resolutions of cameras 1 and 2, which were 0.5 mm/pixel and 2.2 mm/pixel respectively. The coefficient of variation of 20 measurement repetitions averaged 7.6, 12.2, and 4.1 percent for stem diameter, root area, and shoot height, respectively. This result indicates a standard deviation of 0.23 mm for a 3.0 mm stem diameter.

The few seedlings which showed the largest deviations in measured parameters were characterized either by needles extending down past the root collar, or by roots bent upward past the root collar, or both. The subroutine which located the root collar performed inconsistently on such seedlings. A few of these seedlings could not be graded.

In subsequent work, projected shoot area was measured, allowing calculation of shoot/root area ratio. Though not tested, we anticipate a correlation between projected area and mass, allowing fast and nondestructive estimation of conventional shoot/root mass ratio. Calculation of the sturdiness ratio (diameter/height) has also been implemented and could provide another parameter for classification.

The measurement precision demonstrated by the algorithm suggests use for classification of seedlings into several acceptable grades. Additional grade definitions could be optimized for specific planting sites. Further, we expect that the comprehensive statistics collected in a commercial implementation would make machine vision grading a valuable nursery management and research tool.

The research described was implemented on a 240 X 256 pixel resolution camera/computer system which was the industry standard at the time of purchase (1984). Systems with 512 X 512 pixel resolution are common today, and the trend toward increased resolution is expected to continue. New systems, with improved architectures and faster central processing units, offer an increase in measurement precision as well as reduced processing time.

The two-camera configuration used in this investigation could be replaced with a single-camera 1024 X 1024 pixel system to yield identical diameter resolution, quadruple height resolution, and 16 times the area resolution. In such a configuration, the amount of raw data (pixels) would increase by a factor of eight. A large percentage of the image would be background, however, and would not require processing.

Further work is being performed in seedling classification and measurement of container grown seedlings. Alternative decision functions, including statistical classifiers, are being investigated for improved classification performance. Plug-surface root-area measurement of container grown seedlings (after extraction) requires segmentation of the roots from the growth medium with special lighting and image processing. Verification of correct plug shape might also be of value.

SUMMARY AND CONCLUSIONS

This study has demonstrated that machine vision can provide accurate production-rate grading of harvested bare-root pine seedlings. Singulated seedlings were transported on a conveyor belt, with shoot orientation and root collar position loosely constrained. Seedlings were classified as acceptable or cull on the basis of stem diameter, shoot height, and projected root area. Tests with loblolly pine seedlings revealed excellent system performance. Seedlings were graded in approximately 0.25 seconds, with an average classification error rate of 5.7 percent. These results exceed manual grading performance, which typically requires one second per seedling with an error rate of seven to ten percent. Misclassification was largely due to seedlings with borderline diameter and/or root area, and the occurrence of branches or roots in the root collar zone. Measurement precision was adequate for seedling classification into several grades, suitable for specific planting sites. The technology promises increases in both speed and measurement accuracy.

DISCLAIMER

Reference to commercial products or trade names is made with the understanding that no discrimination is intended or endorsement implied.

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