

# Prototyping an automated lumber processing system

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## Abstract

The Automated Lumber Processing System (ALPS) is a multi-disciplinary continuing effort directed toward increasing the yield obtained from hardwood lumber boards during their process of remanufacture into secondary products (furniture, etc.). ALPS proposes a nondestructive vision system to scan a board for its dimension and the location and expanse of surface defects on it. This information is then used to determine an efficient placement of the desired wood parts. Finally, a laser path planning algorithm is used to obtain an efficient path for the Computer Numeric Controlled (CNC) laser to follow to effectively punch out desired parts. While some individual subsystems of ALPS have been reported separately in previous communications, our recent success with the vision system required by ALPS has made the integration of the individual modules of ALPS possible. The vision subsystem and some other subsystems have been prototyped at West Virginia University. Recent efforts have been directed toward integrating these subsystems with the material-handling and laser cut-up system at Michigan State University in an attempt to create a fully functional prototype of ALPS.

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A substantial portion of the hardwood lumber industry is devoted to the processing of lumber into secondary wood products (like furniture parts). Hardwood boards are typically remanufactured into smaller parts by a series of rip and crosscuts. These cuts yield pieces, in accordance with the manufacturers cutting bill, that are free of defective area. The entire process is labor intensive and results in a substantial loss of valuable lumber. These losses increase with operator fatigue and inexperience. One system directed toward overcoming these problems is acronymed ALPS (Automated Lumber Processing Sys-

tem) and has been proposed by McMillin et al. (21). The proposed ALPS system, shown in Figure 1, consists of six subsystems:

1. A material-handling system (12,27).
2. A computer vision system to determine defects on boards using nondestructive scanning methods (2-4,17,19).
3. A computer program to assign NHLA grades to lumber (14).
4. A yield optimization program to compute an efficient cutting placement strategy based on a manufacturer's cutting bill (13,15,16,18).
5. A path optimization program to compute an efficient path for the laser to follow in its attempt to effectively punch out the cuttings placed by the yield optimization program (13).
6. A high-powered laser cutting system to cut the parts placed on the board (1,10,22).

There are two primary advantages of ALPS. First, the use of lasers allows any shaped cutting to be effectively punched out. Second, the use of computers ensures a consistently high yield. Secondary benefits like reduced kerf loss (the laser requires a kerf of less than 1/16 in.) further add to the attractiveness of the ALPS package. Feasibility studies on ALPS have shown it to be economically attractive (7-9,20,24).

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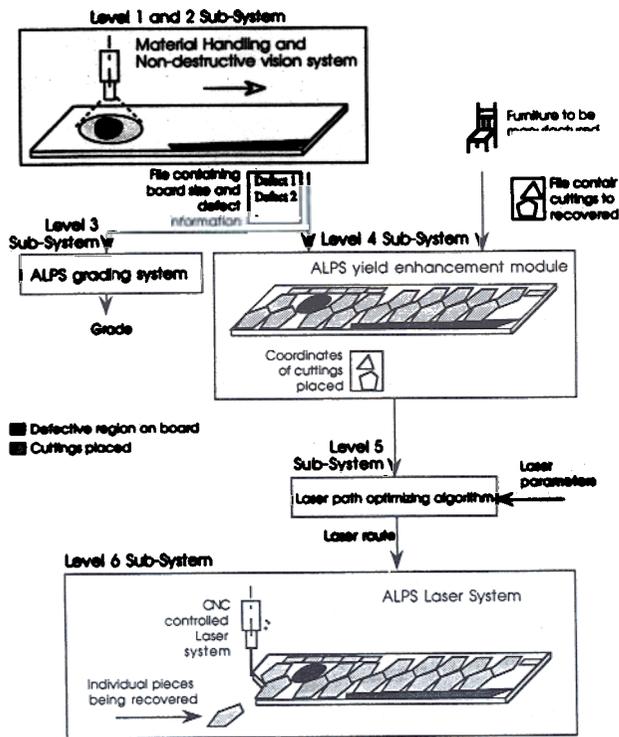


Figure 1.—Flow of information and material in the ALPS system.

This paper describes the subsystems of ALPS and the efforts toward integrating them to create a fully functional prototype of ALPS. Some of these subsystems have been separately reported in the literature and are therefore only briefly described herein.

### Level 1 subsystem: the ALPS material-handling system

The ALPS material-handling system, as the name implies, is responsible for moving the material through the manufacturing pipeline. It consists of a contiguous 34-foot-long conveyor (16 in. for board coming in, 16 in. for board going out, and 2 in. for the laser station), which is designed to handle boards up to 16 feet in length. Figure 2 shows a sketch of the material-handling system. The system has two degrees of freedom. The  $x$ -axis is the axis of the conveyor and the  $y$ -axis is the axis of the laser (orthogonal to the  $x$ -axis). Movement along these axes is obtained by a stepper motor (laser) and a synchronous motor (conveyor) interfaced to a computer through an indexer card. All commands to the motors are directed through the indexer card.

The material-handling system and the other subsystems in the ALPS prototype are controlled using an Intel 486 based computer as shown in Figure 3. A board to be remanufactured is placed on the conveyor belt (Fig. 2). The conveyor belt is specially coated to provide a sticky surface to avoid the need for clamping the board. Remanufacturing of the board begins by the ALPS program bringing successive 1-foot sections of the board under the camera view (which is fixed).

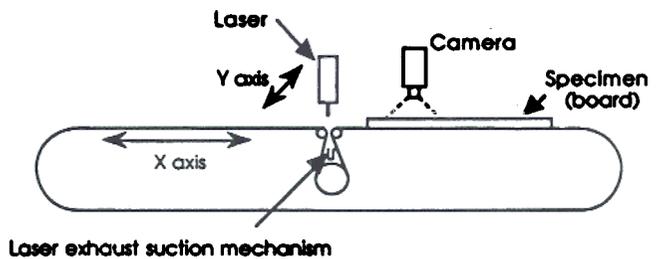


Figure 2.—A simplified view of the ALPS material-handling system.

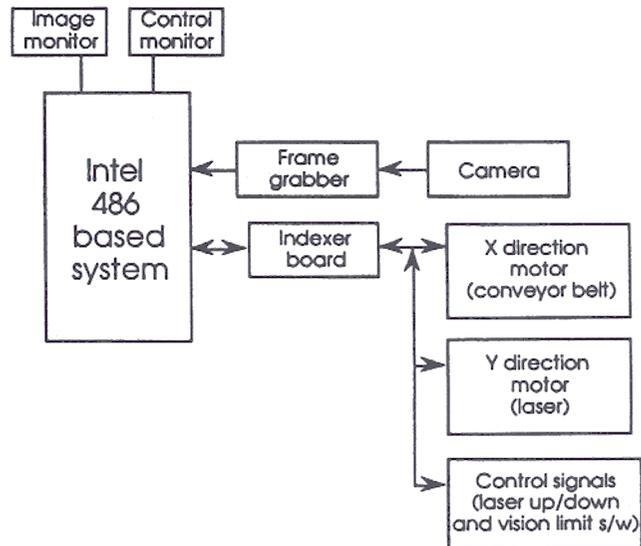


Figure 3.—The ALPS system block diagram.

The image of the section currently under the camera view is captured using a frame grabber and this image is then processed by the vision system as described later. While the vision system is processing the frame just captured, the material-handling system (only the  $x$ -axis) is moved so that the next section is ready under the camera view. Once an entire board is processed, the yield and path optimizing algorithms are invoked, resulting in an efficient path for the laser to follow in an attempt to punch out the cuttings specified by the cutting bill.

The actual laser cutting process requires movement of both the  $x$ -axis and the  $y$ -axis of the material-handling system. Note that each axis can only move in either the horizontal or vertical direction. A cut in the horizontal or vertical direction is achieved by moving the  $x$ -axis or the  $y$ -axis only while the laser beam is on. A diagonal cut, however, requires the motion of both the axes. The velocity of the axes are adjusted in proportion to the projected length of the diagonal on the  $x$ - and  $y$ -axes, respectively.

At the present time, the material-handling system can move at the maximum speed of 600 inches per minute. While actual industry speeds vary, this speed

is sufficient for our goal of demonstrating the ALPS concept.

### Level 2 subsystem: the ALPS vision system

The vision system forms the front end of ALPS. It is responsible for obtaining the dimension of a board and the location and expanse of the defects on it. This information is required by the next subsystem – the yield optimization module.

The vision system required by ALPS is complex. Complexities arise primarily because of the presence of grain marks, by the marked discoloration between heartwood and sapwood, and by the differences in tone and texture across different species and even in the same species from different geographic regions. Previous attempts (2-4) toward a vision system for ALPS have employed a controlled environment to minimize these effects. A board is viewed as several small disjoint rectangles, and statistical measures

(such as tone and texture of wood) are then used to classify each of these disjoint rectangles into one of the following categories: clear wood, hole, wane, etc. (2-4). The approach adopted by the ALPS vision system is different from these established paradigms.

### Obtaining the perimeter and defect location

Our goals in designing a vision system for ALPS were those that are desirable in any implementation – the system should be fast, inexpensive, and impose a minimal amount of control over the environment. The equipment used by the vision system is indeed modest. It includes a 256 level gray scale area camera of resolution 512 by 480 pixels distributed over a 1-foot by 8-inch section of a board, a 30 frames/second frame grabber, and four ordinary fluorescent lights to provide the proper illumination.

The first step performed by vision systems in general is segmentation. Segmentation is a process by which an image is decomposed into meaningful regions. For example, in the case of ALPS, a segmentation ideally should result in three regions. These regions would belong to the background (part of the material-handling system, like the conveyor on which a board lies), the clear part on the board, and the defective part on the board. Conventional approaches to segmentation are many and varied. Commonly, an operation called edge or contour detection is used (23). An edge typically marks out the boundary of each meaningful region that is present in an image and is little more than regions with high intensity variation. In this form, however, the grain marks present on the board would also manifest themselves. Contour detection is the next logical step, where the search for edges is constrained to the particular contour we seek. To seek the outline of a board for example, one would look for a rectangular shape. However, this method is still prone to the localized variations in an image. The main reason that localized variations manifest themselves is that these segmentation operators look at an extremely small area of an image. In contrast, the ALPS image analysis system uses dynamic thresholds for image segmentation. The ALPS process assigns a range of gray levels to each region that composes an image. In our case, a typical image (Fig. 4a) has three regions (the small region appearing at the left is due to noise and is ignored in subsequent discussion): the background, the clear board area, and the defective area. Assigning a range of gray levels to each of these three regions results in removing the variations that may exist in clear wood (grain marks, etc.). To establish the potency of threshold-based segmentation, consider Figure 4b, which shows the histogram of the board section shown in Figure 4a. The histogram shows three distinct regions, as indicated. Figure 4c shows the result of segmenting the image based on the thresholds of Figure 4b. Notice that the resulting image clearly shows the location of the defects and the board perimeter. An assumption we make is that all defects are darker than the clear wood. This does not impose any substantial limitations save that sound

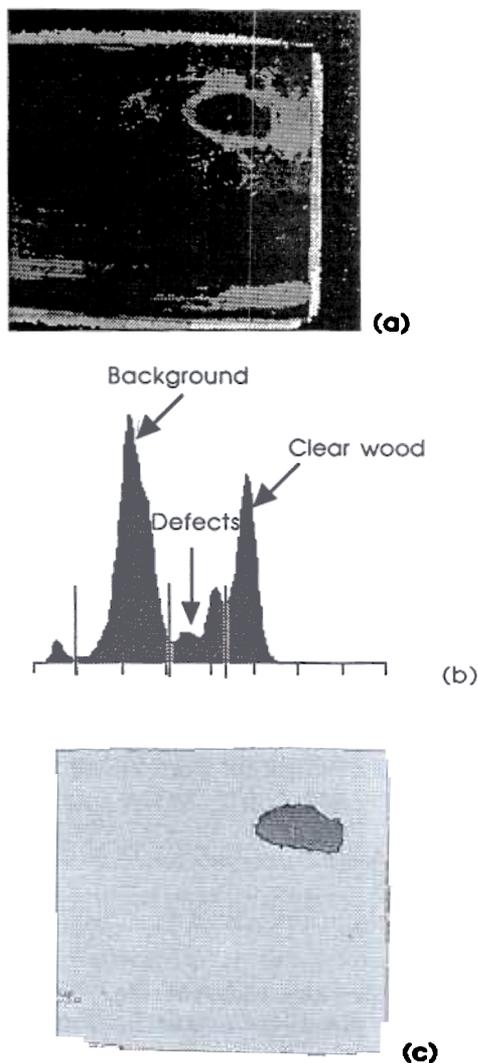


Figure 4.—(a) Section of a sample board; (b) histogram of the section; (c) the segmented image.

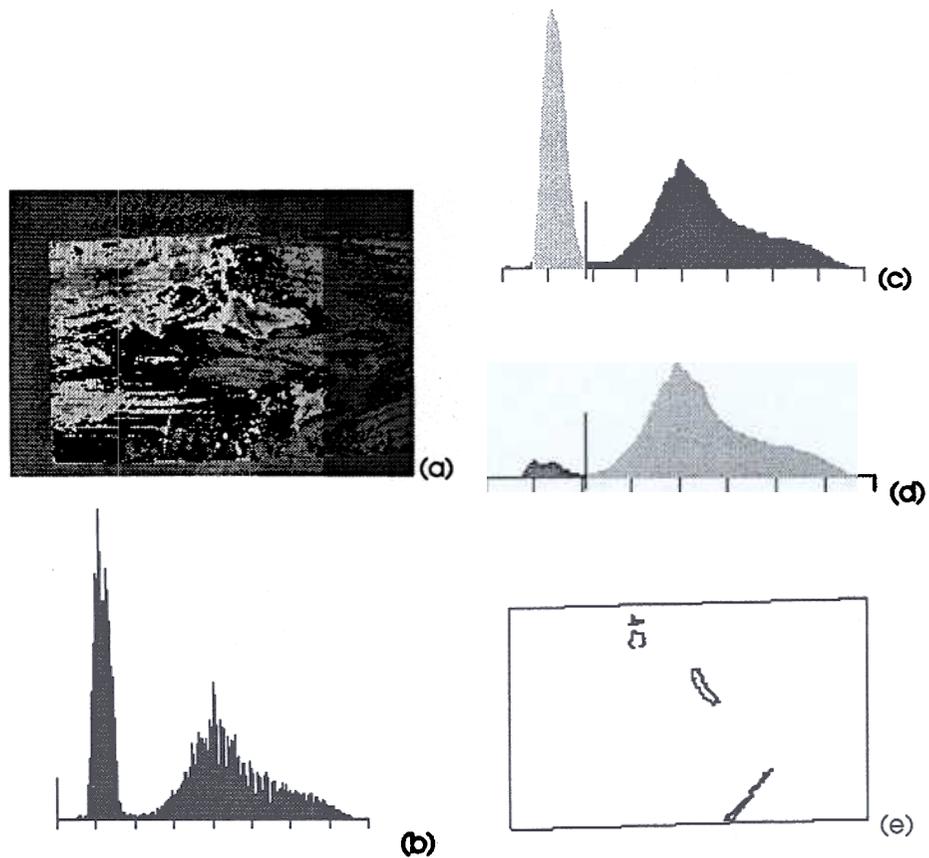


Figure 5.— (a) Sample board; (b) histogram requiring two-stage thresholding; (c) removing the background from the board; (d) removing the clear from the defective part; and (e) the segmented board.

knots or decay are not entirely obtainable. This shortcoming notwithstanding, the process results in an extremely fast determination of the perimeter of the board and location of the defects.

We obtain these multiple thresholds required for the segmentation using neural networks trained with back propagation (25). These networks consist of extremely simple neuron-like elements massively interconnected; the computational ability of the network arises from the collective computational abilities of these simple elements. Typically, they are trained with some known inputs and outputs — a process by which the influence of one neuron over another is determined. For more extensive details on how these multiple thresholds are determined, the reader is referred to a previous report (19).

In reality, it often occurs that three distinct regions are not available from the histogram. The procedure is then extended so as to perform the segmentation in two phases as shown in Figure 5. The first stage of segmentation tries to remove the board from the background (Fig. 5c) and the second phase separates the clear board from the defective board (Fig. 5d). Figure 5e shows the segmented image based on this two-stage segmentation process.

Once the entire board is scanned in this way, the ALPS vision system allows the user to add (if the user feels a defect has been missed) or delete defects (if the defect is acceptable for a particular situation), using a

mouse. Once this editing phase is over, ALPS passes the board data to the next subsystem for packing the cuttings in accordance with the manufacturer's cutting bill.

### Level 3 subsystem: the ALPS lumber grading system

The ALPS grading system (13) is a computer program that assigns NHLA grades to lumber, and uses both faces in the grading process. It has the flexibility to incorporate species-dependent rules. As input, the grading system accepts data from the vision system and as output assigns one of the following grades: FAS, Selects, No. 1 Common, No. 2A Common, No. 3A Common, and below grade. For proper grading, classification of each defect is required. At present, we have developed a neural-network-based method for classifying defects into one of the five categories commonly found on lumber: wane, knots, holes, checks, and splits. However, these categories are not enough for lumber grading and consequently grading abilities are not currently incorporated into the ALPS prototype.

### Level 4 subsystem: the ALPS yield optimization program

Once the dimension of the board and the location and expanse of the defects are known, a yield optimization module is invoked to remanufacture the board into pieces as described by the manufacturer's cutting

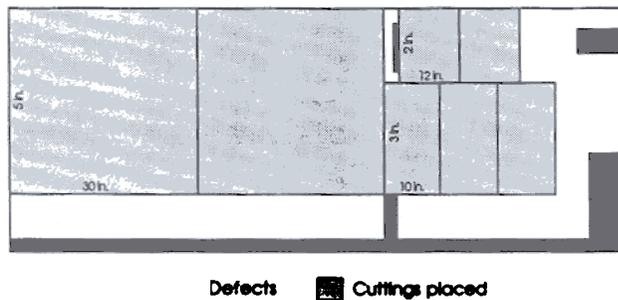


Figure 6.—The cuttings placed by the ALPS yield optimizing subsystem

bill. The randomness of the size of the pieces required and the board precludes an exact mathematical optimization technique. The recovery of these pieces using a laser allows further flexibility in positioning the cuttings, unlike rip and crosscut systems (6,7,26,28).

In the absence of exact mathematical optimization techniques, we use a heuristic algorithm to determine the placement of the cuttings. The concept used is that the placement of the cuttings, if optimized locally, will result in global optimization to some extent. Thus, the ALPS yield enhancement program first finds the largest clear area on a board. The various cuttings in the cutting bill are then evaluated for possible placement in this clear area. The cuttings placed in this clear area are the ones that maximize the cost function. The program supports two different cost functions: value and area. Once this area is packed with cuttings, it is masked off as a defective region and the process is repeated until no more cuttings can be placed.

The ALPS yield enhancement program has been reported in a great amount of detail in other articles (13,15) and the reader is referred to them for exact implementation details. The output of the yield optimization program is shown in Figure 6. Once these cuttings are placed, the path optimizing program charts out an efficient path for the laser to follow in the cutting or marking procedure.

#### Level 5 subsystem: the ALPS laser path optimization system

The ALPS laser path optimization program is responsible for charting out the exact route the laser should follow in an effort to recover the cuttings placed by the yield enhancement algorithm. The path optimization program requires, as input, a description of the board, defects, cuttings, and the laser system parameters. The system parameters are input as two different numbers: the laser speed (ft./sec.) and the axes reposition time (sec.). The board information is received as two lists: the first describes the board and defects; the second describes the cutting placement.

The system parameters are required because the application of a routing strategy with many direction changes in a system with slow-moving axes would be detrimental to the overall cutting time. Thus, for this

type of system, a path with a minimal number of direction changes is desired. On the other hand, low-power laser systems require slow cutting speeds. In this case, it is desired to have the shortest possible distance. The laser path optimization subsystem can thus produce a path that is optimized for a given system.

In what follows, we will refer to the boundary of a cutting as edges and the point of intersection of two edges as a node. The problem of recovering the cuttings from the board is then similar to traveling all the edges (not all the nodes). The ALPS path optimization program applies graph theory to find the optimal laser path based upon system parameters. The optimal path along a set of edges would be one that traverses every edge exactly once. This type of path is known as a Euler line or tour, and a graph containing one is a Euler graph (5). If every vertex in a connected graph is even, then a continuous path exists that traverses every edge only once and returns to the starting node. For an even number of edges, every entrance has a corresponding exit. An odd number of edges will leave one entrance without a matching exit. It will, therefore, be impossible to leave this node after it is entered. To resolve the problem of an odd graph, secondary edges are added to the graph to connect the odd nodes, thus making them even.

Since the length of the primary edges is fixed, the total length is essentially a function of the secondary edge length. Thus, reducing the sum of the secondary edge lengths reduces the overall laser path distance. The strategy followed by the ALPS path optimizing algorithm is determined by calculating the total time required to minimize both cost functions: 1) minimizing the number of direction changes; and 2) minimizing the total length traveled. It is impossible to calculate every possible combination and choose the shortest path due to the time considerations. For this reason, an optimal method of choosing the secondary connectivity must be chosen. The method used is as follows:

1. Determine the distance between the first node in the odd node list and all other nodes.
2. Add a connection between the combination that results in the shortest distance.
  - a) If two combinations give the shortest distance, choose the one that results in no directional change, if possible.
  - b) If both result in directional changes, the choice is arbitrary. This algorithm chooses the first combination encountered.
- 3) Remove the two nodes from the odd node list.

This process is repeated until no nodes remain on the list. For minimizing the total distance traveled, secondary edges are added as the path is formed. The node closest to the current laser position is chosen as the starting point. As each step in the path is formed, two pieces of information are recorded: the path length and the number of direction changes. After each optimization method has been performed on a cutting

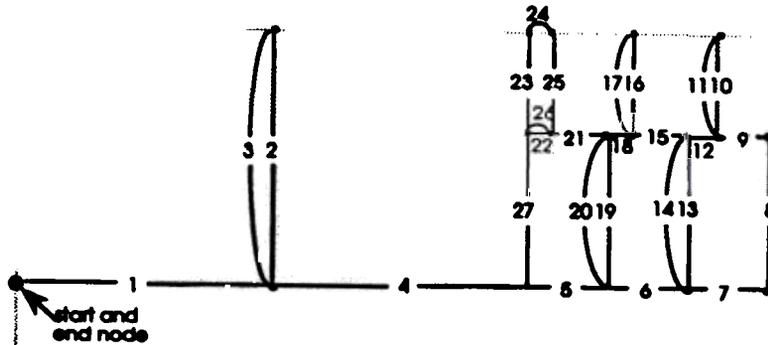


Figure 7.—The output of the ALPS path optimizing subsystem.

layout, this information is used to calculate the total time required to extract the pieces, based upon system parameters.

$$\text{Total time (sec.)} = \text{direction changes} \times \text{table time (sec.)} + \text{path length (ft.)} / \text{laser speed (ft./sec.)}$$

The path resulting in the shortest time is then sent to the laser for processing. Figure 7 shows the output of the path optimizing algorithm of ALPS for the cutting placement shown in Figure 6. The numbers on the edges indicate the sequence in which each edge was traversed.

#### Level 6 subsystem: the ALPS laser system

The laser subsystem allows the cuttings placed on a board to be recovered in a "punch-cut" fashion. To this end, a radio-frequency excited, 2800-watt carbon dioxide laser, operating in TEM<sub>01</sub> mode, equipped with a circular polarizer is used. The laser subsystem can be raised up or down along the z-axis to allow for focusing the nozzle beam spot irrespective of any curvature or warpage of the wood. A pneumatically controlled floating head that rolls on three steel balls, capable of adopting both transmissive and reflective focusing heads, has been designed to automatically adjust the gap between nozzle and wood surface.

The actual recovery of the cuttings is achieved as described in the previous sections. The material-handling system motors move the board while the laser beam is turned on or off, corresponding to whether an edge must be cut or not.

At present, the highest feed rates for clean, narrow, and through cuts obtained in our laboratory for basswood, black cherry, and black walnut are 300, 220, and 200 inches per minute, respectively. (Fig. 8 shows the experimentally obtained reciprocal relationship between the cutting speed and depth of cut for different density wood samples.) The cut surfaces are being studied by using optical and electron microscopy. Under optimum cutting conditions, the charred laser-cut surfaces are light brown in color. High temperatures, on the order of 3000°K, as determined by the continuum nature of the plasma studied by using emission spectroscopy, suggest that high-temperature pyrolysis of wood takes place, resulting in a lower

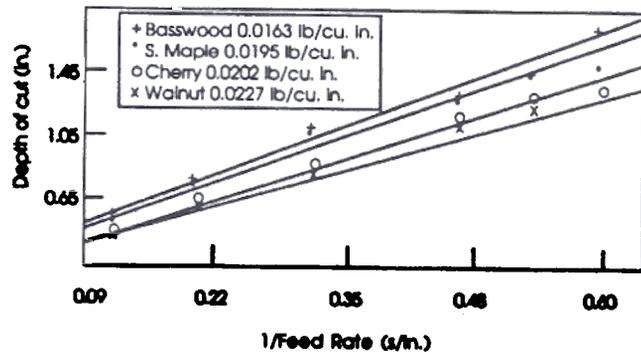


Figure 8.—Reciprocal of cutting speed vs. depth of cut for different densities of wood.

percentage of char yield. Use of oxygen and a supersonic gas nozzle were found to be highly beneficial in making deep cuts.

#### Performance expectation

The ALPS prototype has been completely integrated and built. The complete system block diagram is shown in Figure 3. However, the performance of the system as a whole can only be known after extensive experimentation. We present below the results of the individual modules of ALPS that were tested after their development.

The proposed vision system concept has been implemented at West Virginia University. Using neural networks simulated in software, we have been able to achieve a processing speed of up to 10 lineal feet per minute and an accuracy of defect location of greater than 95 percent. Since neural networks present the advantages of parallelism when implemented in hardware, this speed will substantially increase as neural network hardware becomes available. The ever-increasing speed and decreasing cost of computers should also allow for the realization of higher speeds.

Studies conducted to date (7-11,20,24) have shown ALPS to be an economically feasible method of furniture remanufacturing. Table 1 shows an overall improvement in yield by 15.5 percent for the ALPS system compared to well-managed, conventional crosscut-first dimension plants in five different tests

using three different species. The production of the longest parts were more than doubled, with an average increase of 109 percent. The production of solid parts in comparison to narrower glued-up parts was increased by an average of 50 percent in the five tests. There was a wide variability in results depending on the lumber quality, cutting sizes, and order. However, the total yield, longest parts, and solids were consistently positive for the ALPS program.

This substantial amount of savings in valuable raw material can quickly offset the cost of installing the new system. Equally attractive is the fact that a production mill could realize larger profits by reducing the grade of lumber it uses rather than by increasing the yield of a higher grade. A polygonal yield enhancement program has also been developed for inclusion into the ALPS prototype (18). Since furniture parts are most often nonrectangular, it is anticipated that a comparison of yield based on polygonal cuttings should further improve the yield obtained.

Table 2 shows the net present value (NPV) and the internal rate of return (IRR), quantitatively. These figures indicate that the best economic returns come when higher value species are processed in large volumes. With the cost of laser equipment decreasing and with rapid development in the fields of robotics and laser technology, ALPS promises to be an economically attractive proposition for tomorrow's furniture manufacturing.

#### Conclusion and future work

This paper presented the efforts directed toward realizing a prototype of the Automated Lumber Processing System (ALPS). A new approach to developing a vision system for the automated determination of the lumber board dimension and location of surface defects was presented. The system completes all the essential modules of ALPS required for its demonstration as a feasible means of future wood remanufacturing. The advantages of the proposed vision system are many. Primarily amongst these are a species indepen-

dent form of processing, the use of a high level of abstraction to achieve faster processing, and the relatively low cost of the vision system. Specifically, the hardware of the prototype vision system that has been developed at West Virginia University would cost less than \$5,000 to implement! Though speeds of up to 10 feet per minute may not be sufficient for the industry, the availability of increased and inexpensive computing power should allow the proposed modified vision system to perform up to the expectations of a 'real time' vision system. We have also developed a neural network-based method for classifying these defects into one of the five categories commonly found on lumber: wane, knots, holes, checks, and splits. Continued research is directed toward additional types of defect classification and the eventual addition of the grading program to automatically determine the grade of a lumber board.

A live demonstration of the ALPS prototype was successfully presented to the industry and academia on Nov. 6, 1991, at Michigan State University. The prototype should also allow further studies on automated furniture part remanufacturing.

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TABLE 1. - Results of five factory tests showing total yield, longest part, and solid part recovery improvement of ALPS.

	Total yield ALPS Improvement	Longest solid part ALPS part increase	Solid part ALPS increase
		(%)	
Walnut I	29.5	1	64.5
Walnut II	16.0	208	33.9
Oak I	13.4	124	47.2
Oak II	13.5	36	9.8
Cherry	5.1	175	95.4
Average	15.5	109	50.2

TABLE 2. - Net present value (NPV) and internal rate of return (IRR) with ALPS.

	30 MBF/day		5 MBF/day	
	NPV	IRR	NPV	IRR
	(\$)	(%)	(\$)	(%)
Red oak	1,398,500	56.4	-60,210	5.5
Soft maple	776,100	37.3	164,000	-2.8

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