Control of Manufacturing Processes and Robotic Systems

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edited by

DAVID E. HARDT
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

WAYNE J. BOOK
GEORGIA INSTITUTE OF TECHNOLOGY

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N. Y. 10017

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FOREWORD

This volume is a collection of papers centered around the theme of application of dynamics systems and control techniques to problems in manufacturing. This is addressed here in the context of manufacturing processes and robotic manipulators and systems.

In the first three sections the processes of cutting, welding and forming are considered. Included are papers addressing novel problems in wood as well as more traditional metal cutting. These efforts reflect the need to improve processes where conventional numerical control is inadequate or inappropriate to the manufacturing task at hand. The second section deals with problems of weld process control. With the advent of robotic welding systems, the need for closed-loop control of weld attributes in real-time has become increasingly evident, and these papers address the range of problems encountered from modelling and sensing to real-time control.

The third section involves processes for forming metals. This is an area where control has not traditionally been a part of the process, but recent work has illustrated the obvious utility of in-process measurements for closed-loop identification and control. The use of control here is unique and bears little resemblence to conventional linear regulators, but the motivation for use of feedback is the same as with all applications: maintaining a desired output in the face of an uncertain system and system environment.

Two sections on research related to robots and manufacturing are included. In these, the issues of basic machine design, machine control and task modelling are addressed in the context of both specific manufacturing problems and for general problems of robotic manipulation. These problems are considered at the individual component level, the robot level and the manufacturing cell level, indicating the range of dynamics and control problems presented by robotic systems in manufacturing.

All of these papers were presented at a symposium of the same name at the 1983 Winter Annual Meeting, and the time and energy of a score of individuals was necessary for its success. Those deserving special mention are Profs. Neville Hogan and Warren Seering of M.I.T. for organization of the fourth section (on Robotics) and Prof. Kim Stelson of the University of Minnesota, for assisting in the organization of the third section (on Metal Forming). In addition, thanks are due the many patient reviewers of these papers whose critical comments have contributed to the quality of this volume.

David E. Hardt
Wayne J. Book

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M. D. McMillen, Technical Staff
TRW, Inc.
Tacoma, Washington

C. L. Nachtigal*, Project Manager
Weyerhaeuser Company
Tacoma, Washington

D. E. Hardt, Assistant Professor of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT

The need for automation in lumber manufacturing is becoming more and more apparent as the margin between raw material cost and finished product price is diminishing. The principal advantages are increased recovery and increased production rate. In order to realize the full potential of the latter, high-speed longitudinal lumber processing systems are a must. This paper discusses two innovative concepts aimed at the development of a high-performance longitudinal lumber manufacturing machine center. These two concepts are: 1) incorporation of a laterally slewed chipping head in manufacturing boards from center cants; 2) in-process control of disturbances during the cutting of any given workpiece. In-process error sensing is accomplished by using a TV camera scanning system. Simulation results for position offset and for skew angle errors are presented. Three different levels of sophistication of the control algorithm were studied and are represented in the results displayed in this paper.

BACKGROUND

The lumber manufacturing industry is awakening to the realization that human operators and manual positioning methods cannot survive in an atmosphere of ever increasing raw materials cost. Optoelectronic scanners will become an essential ingredient in the lumber factory of the future. At present we are witnessing their increased usage in gathering size, shape and position information in the lumber mill. Minicomputer- and microcomputer-based cutting algorithms are being utilized but are limited by the lack of complete geometry information imposed by the scanners currently in use.

To date all applications of automated scanning and cutting machine centers are based on open-loop control in the sense that the piece part is scanned upstream of the processing zone and the assumption is made that it remains in the same attitude as it is transported up to and through the cutting process. The cutting mechansim is generally equipped with a feedback transducer to accomplish accurate positioning and regulation relative to its own framework. But the missing link in current automated machine centers is closure of the overall loop. This necessitates monitoring and correcting (if necessary) the relative position between cutter and workpiece. This paper presents a concept and simulation results for such an overall closed-loop process which, to the authors' knowledge, represents the first disclosure of closed-loop lumber manufacturing.

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*Affiliate Professor of Mechanical Engineering, University of Washington, Seattle Washington

Today's Lumber Mill

Most lumber manufacturing is or will soon be carried out by a so-called small-log mill. This designation loosely specifies logs in the small-end diameter range of 115 mm to 250 or 300 mm. Typically, six cutting operations as shown in Figure 1 are employed to produce green lumber, [1][1]. Some of these operations, such as board edging, (4), and remanufacturing, (5), are wood machining processes which employ a chipping head rather than a saw. The primary breakdown process, (2), frequently makes use of chipping heads to reduce the nonlumber-producing outside slabs to chips for paper making.

The size and therefore the profitability of each piece part is quite small; thus, the present and future small-log mill demands a high production rate if it is to survive. Therefore, this type of mill tends to be constructed along longitudinal flow lines with transverse flow kept to a minimum. Automated cutting processes (if present) consist of noncontact optoelectronic scanners located upstream of and in line with the cutting machinery. Only minimum information is obtainable with state-of-the-art scanners; for example, beam-breaking scanners which sense the log diameter at closely spaced cross-sections. Because it is desirable to keep the piece part in motion throughout the scanning/computing/conveying/cutting cycle, the sawline is parallel with the conveying direction. This orientation is normally not the desired skew direction from the standpoint of maximizing the product value of the piece part. If the piece part is to be optimally processed, it must be repositioned on its conveyor after scanning and before arriving at the cutting zone. But this requires stopping the forward progress of the piece or constructing a complex and costly machine structure which is able to position the piece laterally while in motion at conveying speeds of 1.3 to 1.8 m/s.

One method of circumventing the repositioning problem is the suboptimal solution of simply positioning the cutting tool in the best offset location relative to each piece. This strategy foregoes the additional lumber recovery attainable if the skew angle could also be adjusted. Another method is an end-dogging frame which spikes into the leading and trailing ends of the log and is arranged so that the two ends of the frame can be independently shifted laterally after scanning. Still another approach is to stop the piece in the scanning zone and then convey it in a transverse direction into the correct skew and offset position just upstream of the cutting mechanism. This method is undesirable from the standpoint of high productivity but some available scanners require transverse displacement for completing the scan. Thus it is convenient to impart the desired skew and offset position to the piece in conjunction with its transverse motion.

Machine center vendors in the forest products industry are just beginning to recognize the required synergism between the scanning/computing/transporting/cutting processes and their role in meeting the requirement for high production rates. An emerging machine center concept which embraces this synergism is described in the next section.

Emerging Technology

The combination of high throughput rates and a longitudinal[2] scanner has resulted in the development of a positionable cutting tool concept and a commercially available automated board edging machine, [2,3]. This approach, wherein the cutting tool is continuously servo-positioned to accommodate the skew positioning variable is called "slewing the cutting tool" by the authors of this paper. Figure 2 shows the slewing cutting tool concept applied to the cant breakdown process. (See Figure 1, item (3).)

To complete the cant sawing operation, the optimally opened face[3] is forced against a fixed guide bar and is longitudinally transported through a multiple round saw machine called a gang saw. The output of this machine consists of dimension boards of width equal to the height of the cant. (Dimension boards are the so-called 2x4's, 2x6's, 2x8's, etc.)

Three breakdown operations are likely to benefit by the slewing cutting tool development: (1) primary breakdown, (2) cant breakdown, (3) board edging. (An automated board edger using the slewing tool concept has just become available.) These three share the properties of longitudinal cutting and significant potential improvement in board recovery with scanning, optimization and positioning. It is likely that the cant breakdown

[1] Numbers in brackets indicate References.

[2] Scanning while the piece part is conveyed longitudinally past the scanner.

[3] The opening face is often called a Best Opening Face or "BOF."

process will be next in the application of slewing cutting tools to an automated system. Finally, the primary breakdown process will be last. This order is based on the ability to grasp the piece part firmly during the cutting operation. Boards are least difficult, followed by cants, and logs are most difficult because of the absence of cut surfaces. We close this section with a reminder that the slewing cutting tool itself most likely requires closed-loop control of its position relative to its own structural framework, but closed-loop control of the slewed tool process is a higher level usage of the term "closed-loop control." The subsequent sections will show how the practice of slewing the cutting tool enables overall closed-loop control of the process of automated primary and/or secondary breakdown.

CANT CONVERSION SYSTEM

Configuration

In keeping with the the small-log longitudinal flow concept of the previous section, Figure 3 shows a two-step automated cant conversion system. Assume that logs pass through a primary breakdown machine center upstream of the primary scan zone. Immediately after the trailing end of the cant clears the scanner lines of sight, the optimal sawlines are computed while the piece remains in motion at approximately 1.5 m/s. The opening face path of the slewing chipper relative to the cant is embedded in the optimal lumber recovery solution. If it can be assumed that the cant remains stationary relative to the conveyor throughout the scanning/computing/chipping cycle, the preprogrammed chipper path is a valid approach. However, two significant sources of error are present: 1) The conveyor generally includes a series of hold-down rolls which bear on the top face of the cant and tend to steer the cant laterally; 2) the chipper cutting forces are disturbances which cause relocation of the cant on the conveyor.

Existing human operator controlled sawing centers are generally not accurate enough to be sensitive to the errors imparted by these disturbances. However, automated machine centers must be economically justified on the basis of their recovery improvement over manually controlled systems. These errors are significant when measured in terms of their effect on recovery loss from the full potential of the automated and controlled sawing center. As we gain more experience with scanners and cutting algorithms in the forest products industry, each known source of error will become a target for elimination. Thus the closed-loop process articulated in this paper and other related concepts yet to be developed will become increasingly important.

Model

A model of the open-loop cant conversion process of Figure 3 is shown in Figure 4. By "open-loop" we mean the situation where the rescan camera is placed sufficiently far upstream of the slewing chipper so that disturbances occurring during the processing of a particular workpiece cannot be sensed by the rescan sensor and, hence, cannot be controlled. The slewing chipper emerging technology is currently open-loop in spite of the fact that the cutting tool is position-controlled relative to its own mounting framework. If the conveyor between the primary scanners and the chippers transports the workpiece accurately, the rescan camera shown in Figure 3 is not required, and thus the "Coordinate Recovery Algorithm" shown in Figure 4 is trivial - the cant is presented to the chipper in the same relative position as in the primary scanning zone. On the other hand, many mill flow patterns include a transverse conveyor between the primary scan zone and the processing zone. This flow pattern requires a means for recovering the cant coordinates relative to its conveyor. We will show in subsequent sections of this paper that the rescan camera may be used in recovery of the cant coordinates as well as in the role of sensor for overall closed-loop control of the BOF-cutting process.

Referring again to Figure 4, the chipper positioning strategy for the open-loop case is to direct the chipper along a straight line which is skewed relative to the conveying direction. If the conveying speed is constant, the set point to the position servo is a staircase ramp versus time.

The cutting force acting along the thrust direction of the chipper heads and the hold-down and structure dynamic compliances have not been quantified. These unquantified expressions were circumvented in this work by assuming step changes in the offset and/or rotation of the cant. These two degrees of freedom combine to produce the relative displacement. The next section shows how the rescan camera is used to measure relative displacement and close the loop by controlling the chipper position to correct for this type of position disturbance.

ALGORITHMS AND RESULTS

There are two distinct issues which require treatment in providing closed-loop chipper position control with a rescan camera. First, an algorithm must be developed to recover the cant position and set the chipper path based on available rescan data. Second, a means for correcting any relative displacements between the workpiece and chipper must be found. This second attribute provides the closed-loop control for the process.

An approach for utilizing rescan data to provide a chipper position set point is first developed, [5], and is extended to four different closed-loop error correction strategies. These different strategies, ranging from a very simple single transducer strategy to a complex, data-intensive dual transducer strategy are studied as follows:

1. Single Transducer - Simple algorithm (ST-S)
2. Single Transducer - Complex algorithm (ST-C1)
3. Single Transducer - augmented Complex algorithm (ST-C2)
4. Dual Transducer - complete algorithm (DT)

The varied degrees of complexity may be determined by the extent to which each strategy detects, quantifies and corrects in-process gross displacement errors. The relationship between the four strategies is shown in Figure 5.

Full-Profile Coordinate Recovery

To provide closed-loop control of the relative position between the workpiece and chipper, it is apparent that scanning must take place during the chipping process. All the information we have with regard to the cant geometry (and thus the desired Best Opening Face) is stored in the surface cross-sections scanned upstream. The cant must be rescanned before it reaches the chipper to recover the coordinate system and to direct the chipper on the pre-determined path. The closer the rescan is to the chipper, the less susceptible it will be to conveying errors. Ideally the rescan should be located directly at the chipper; however, we must be able to relocate the cant coordinates based on the rescanned points before chipping begins. Since there is error associated with each rescan profile, the more information available before chipping begins, the more accurate is the estimate of the cant position. Thus there is a trade-off between accuracy of recovered cant position and susceptibility to cant displacement between rescan and chipper in choosing the rescan camera placement. Before describing this trade-off further, it is important to fully describe a method for recovering the cant coordinate system.

The initial scan process performed upstream is concerned with gathering geometric data upon which a Best Opening Face solution is based and developing a data base which can be used at the rescan to recover the cant position. This data base consists of a set of values relating the scanned profiles with the corresponding BOF position. First, a single-value characterization of each profile is developed. One possible characterization is the average X-value of the points in the profile scan. This may be associated with the BOF position solution and a "distance to BOF" value determined as shown in Figure 6. A set of these "distance to BOF" values may be passed downstream and associated with corresponding average X-value rescans to determine the BOF position for a profile at the rescan location. Since the calculated BOF is a straight line, the recovered BOF points should lie in a straight line, assuming the rescan profiles exactly match the initial scan profiles. Rescan errors will exist because we cannot guarantee that the same profiles will be rescanned. It has been found that there will be an error of two to five mm between single-point profile characterizations (depending on cant surface qualities) when initial scan and rescan do not overlap. Thus, the rescan data points will not lie in a straight line, but will have a random error deviation about a straight line. This error in rescan information was simulated by a random number generator with zero mean and selectable standard deviations ranging from 0 to 5 mm.

It is necessary to set the chipper path based on the recovered BOF points obtained by rescanning before the cant reaches the chipper. One obvious choice for determining a chipper path is to least-squares fit the gathered points to a line which becomes the recovered BOF line. Since only a small portion of the cant is scanned before chipping begins, any error associated with the recovered BOF line will be increasingly multiplied the further a straight line chipping path is extended. Choosing a straight line chipping path based on this information also ignores all data gathered after chipping begins. It seems wise to utilize all rescan data to continually improve our estimate of where the recovered BOF line lies and accept a small variance in the straightness of the chipping path. Thus every time a new BOF datum point is taken, the least-squares fit should be updated and the chipping path corrected to reflect the new BOF position. If we assume for the moment that no cant displacement errors occur during chipping, variations in the recovered BOF position will decrease with each incremental datum point.

It is essential to develop a method for altering the chipper path to reflect the most recently updated BOF line. Responding too rapidly to new lines will generate an undesirable surface, thus a strategy that effectively filters the new estimates is necessary to yield acceptable results. Aiming at the "better BOF" some distance upstream, we can work towards it without actually having to be there at the next update point. Thus we can vary the sensitivity to the error inherent in the rescan process by adjusting the upstream distance at which the chipper path aims. This "AIMDISTANCE" strategy for adjusting the in-process chipper path is displayed in Figure 7. It is apparent that this strategy may be used for determining the chipper path independent of scan number and placement.

It has been determined that when using the AIMDISTANCE strategy, if at least 500 mm is allowed between a single rescan camera and the chipper (six or more data points before chipping begins), the error between the recovered BOF and the true BOF is acceptable. Figure 8 shows the effect of varying the distance between the rescan and the chipper. The effect of varying the AIMDISTANCE is shown in Figure 9. It must be emphasized that these results (as all results in this paper) are measures of the chipper set point accuracy and do not reflect the dynamics of the servo positioner. Let us assume that with proper actuator selection and control system design, the actual chipper path will approach the command chipper path. Having developed a generalized chipper positioning strategy for rescan data points, the last step to providing closed-loop control is to include a means for correcting in-process gross displacement errors.

<u>**Single Transducer Closed-Loop Strategies**</u>

Three closed-loop strategies were developed for the single camera rescan configuration as shown earlier (Figure 5). In each case, any cant displacement effects the remaining scans and closes the loop on the process as shown in Figure 10. The difference between the three strategies lies in the logic used in the "Coordinate Recovery" block. The first of these, the Single Transducer - Simple algorithm (ST-S), does nothing to quantify in-process gross displacement errors. It merely continues adding data points to the least-squares fit line without regard to their validity. This inherently shifts the least-squares fit line to reflect the new cant position, but the correction is slow and depends on the number of data points gathered before the displacement occurs (the low-pass filter characteristics of a least-squares fit).

Cant gross displacement errors were simulated by adding a step offset and rotation about the chipping point to the incoming BOF values. Three types of error were simulated: leading end offset with rotation, middle cant pure offset, and trailing end offset with rotation. Characteristically, pure offset errors are easier to correct than rotation errors since any angular deviation causes the recovered BOF and actual BOF to diverge. Leading end errors are most important to correct since a good deal of lumber recovery value is lost if no action is taken. For this reason, results are shown for the leading end offset with rotation error only. All simulation results are for a cant velocity of 2.0 m/s, scan rate of 30 Hz, AIMDISTANCE of 200 mm, and random rescan error standard deviation of 2.0 mm. The ST-S error correction for a 5 mm offset with a -2 degree rotation occurring 250 mm into a 5 m cant is shown in Figure 11. Correction is rapid and accurate, with the chipper path brought back within 1.5 mm of the actual BOF in less than a half meter of cant travel. It should be noted that correction of this error type is the strong point of the ST-S strategy since there is very little numerical inertia so early in the process and the negative cant rotation error is quickly corrected as the process continues. Results for all other error types show a pronounced degradation in performance with the ST-S strategy. In light of these further results, it is apparent that a more comprehensive approach to correction of in-process gross displacement errors is necessary.

The Single Transducer - Complex (ST-C) strategies were developed to actively detect gross displacement errors by looking at incoming data points. We know that the rescan BOF points should lie in a straight line, thus once we have a reasonable idea about the orientation of this line we know where incremental data points should lie. If we accept that there will be a certain variability of data points about this line due to random rescan errors, we can watch for excessively deviant points and use them to signal gross displacement errors. This is accomplished by extending the least-squares fit line to the Z-position of the next datum point, and determining the expected X-coordinate. If the datum point differs from the expected value by more than an "acceptable" amount, an error flag is set. A single erred point may not indicate an error since erroneous points are considered, but two consecutive erred points with the same error sign should indicate an error.

Both ST-C strategies are based on calculating an expected next datum point for error detection. The difference between the two strategies lies in the method for correcting an error once it has been detected. The approach taken by the ST-C1 strategy is to begin a new least-squares fit line with the two points which signalled the error.

The new line is extended to the chipper and a new command position is determined. Ensuing data points are added to this new fit line and the variability of the line stabilizes after four or five points. Accuracy of the chipper position command signal for the same offset with rotation error induced earlier (5 mm, -2 degrees at 250 mm into the cut) is shown in Figure 12. Correction is accurate after an initial period of oscillation caused by the deviation of the new least-squares fit line. Leading end errors are in fact corrected more quickly by the ST-S strategy, but the consistent performance of the ST-C1 strategy across all error types demonstrates the superiority of the latter.

The ST-C2 strategy was developed in an effort to reduce the problems associated with beginning a new least-squares fit line when an error is detected. In order to reduce the variability of the new fit line, a pure offset error is assumed until four points have been gathered. Thereafter, the new least-squares BOF line has stabilized to the extent that we may again use the AIMDISTANCE strategy to generate chipper command positions. Results from this error detection strategy were marginally better than the ST-C1 strategy (obviously it performed very well for pure offset errors) and are omitted for brevity.

A Dual Transducer Closed-Loop Strategy

The advantages of actively detecting gross displacement errors are obvious, but attempting to correct errors by starting a new least-squares fit and extrapolating to the chipper is not as accurate as would be desired. Adding another transducer to aid in detection, quantization and correction of these errors is a definite improvement. Placing this second transducer just downstream of the chipper and incorporating its data points into the least-squares fit BOF line will permit interpolation to the chipper and thus a considerably more accurate recovered BOF when an error occurs. The second transducer need only measure the distance to the flat chipped face of the cant and thus need not be a video camera. If the chipper position is monitored with time, a template of the generated cant surface is known and may be used to check measured values. This further extends the ability of the system to detect in-process errors and permits very accurate quantization and correction. Although admittedly complex, this dual transducer algorithm is able to provide the tightest control of the relative cant/chipper position throughout the entire process. The process block diagram is augmented by the addition of the downstream transducer and related logic and is shown in Figure 13. The additional block is only valid when the cant is in view of both transducers. Before the cant reaches the downstream transducer, the ST-C2 strategy is employed. A similar single transducer algorithm is utilized after the cant passes out of the upstream scanner view. Leading end offset with rotation error correction for the DT configuration is shown in Figure 14. The dual transducer performance is consistent across all error types and represents the most effective means of detecting and correcting in-process gross displacement errors.

CONCLUSIONS

Extensive simulation results have shown that in-process closed-loop control is feasible for cant chipping. The AIMDISTANCE strategy has been shown to be quite effective in recovering the BOF position established by an upstream scan. This was extended to the ST-S strategy and proven effective in correcting gross displacement errors occurring early in the chipping process. Addition of logic to check the validity of incoming data points in the ST-C strategies provides error detection and accurate correction (after a brief period of instability) for all error types. Including a second transducer downstream of the chipper allows for more accurate detection, quantization and correction of in-process gross displacement errors throughout the chipping process. All four approaches represent a definite improvement over the open-loop process with the DT configuration providing extremely tight closed-loop control of the relative position between workpiece and chipper. Implementing in-process closed-loop control will result in increased system accuracy and improved secondary breakdown recovery.

All strategies which actively detect errors calculate an expected next datum point value. Actual values are allowed to differ from expected by a certain amount without being flagged. Selection of this "threshold" depends on the characteristics of the scan/rescan accuracy for a given system and certainly effects the performance of the system. (Needless to say, it is undesirable to correct an error which never occurred.)

Further work is recommended in examining the nature of typical error types to aid in their detection. Researching the effect of an AIMDISTANCE which changes during the course of chipping is also recommended. It would be desirable to have a short AIMDISTANCE early in the process to stay near the rapidly changing recovered BOF line and a longer AIMDISTANCE later to diminish sensitivity to rescan errors. Again, it must be emphasized that the results presented are for the set point accuracy and do not consider position servo response. Actual performance will be determined by the ability of the servo-actuated chipper to follow the command input. Also, the time required to compute the new chipper path represents a part of the overall dynamic response issue. The results reported in this paper are based on instantaneous computation time. Further work to include this time effect is recommended.

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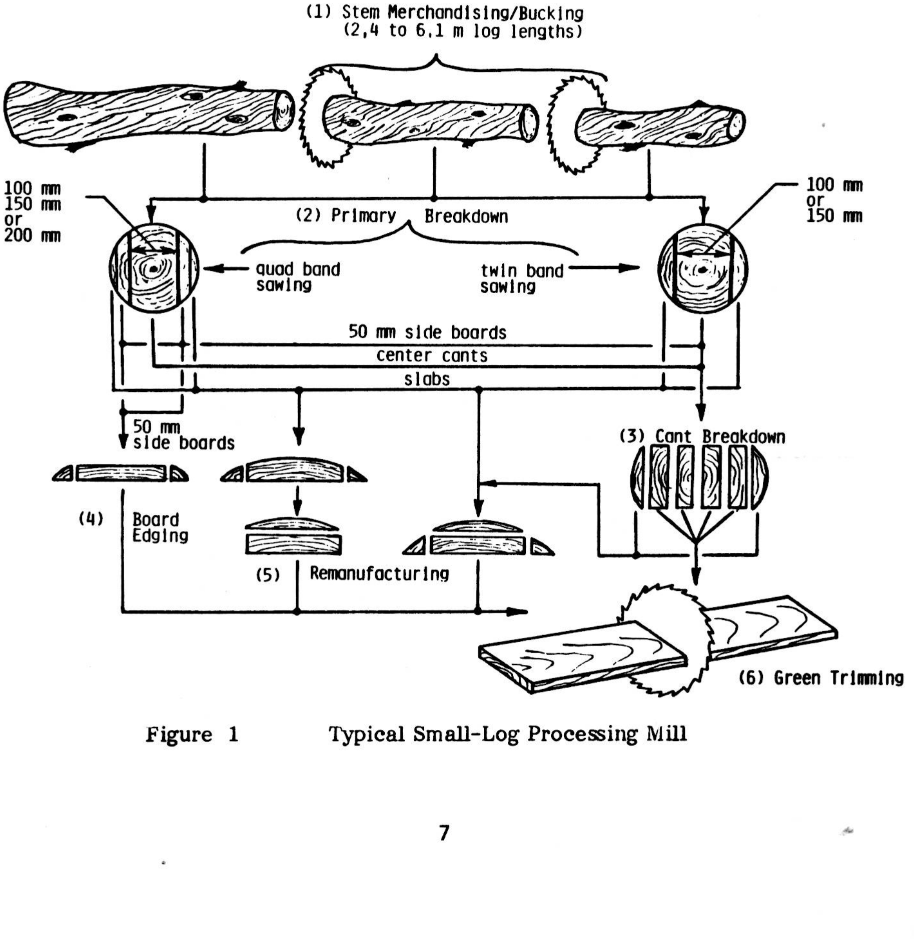

Figure 1 Typical Small-Log Processing Mill

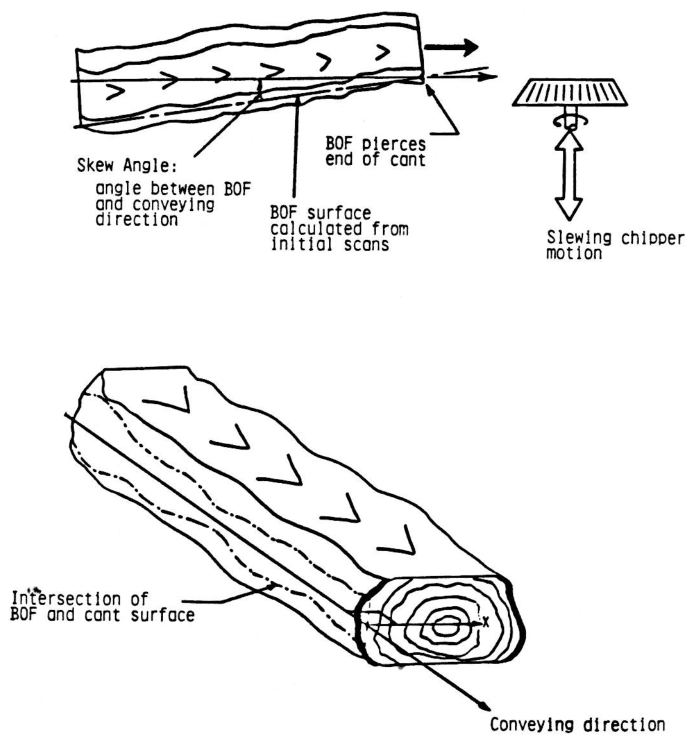

Figure 2 Slewing Chipper Applied to Cant Conversion

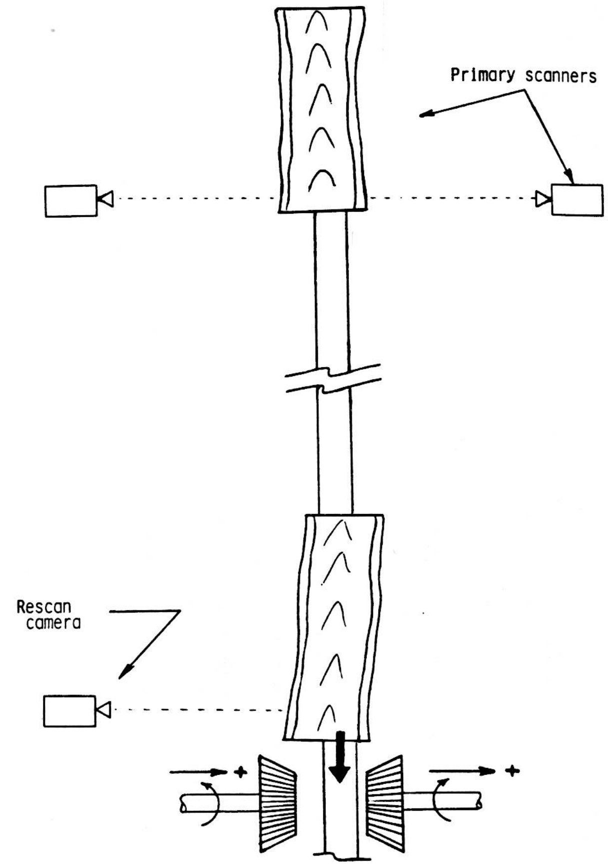

Figure 3 In-Line Cant Conversion

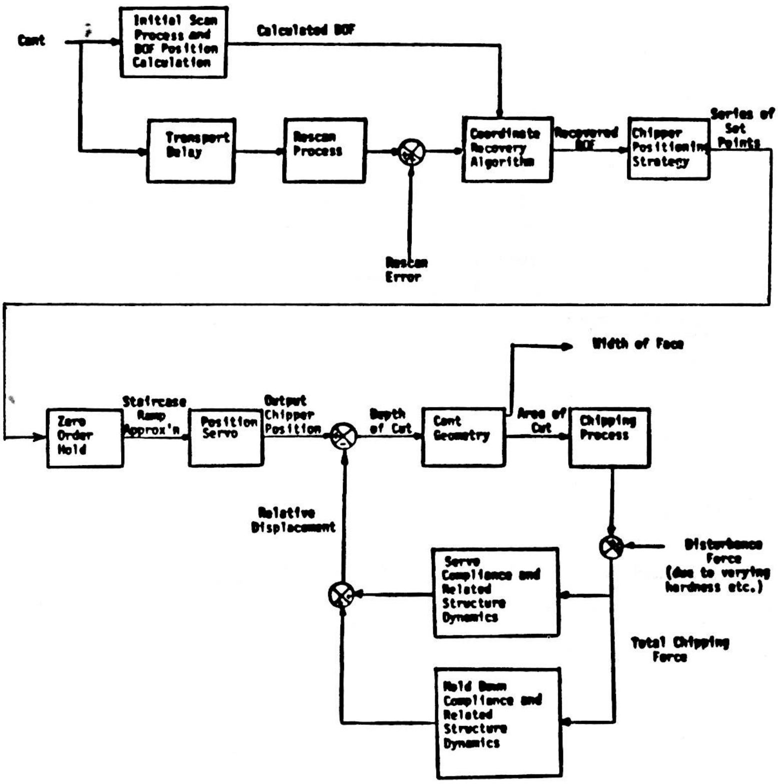

Figure 4 The Open-Loop Process Block Diagram

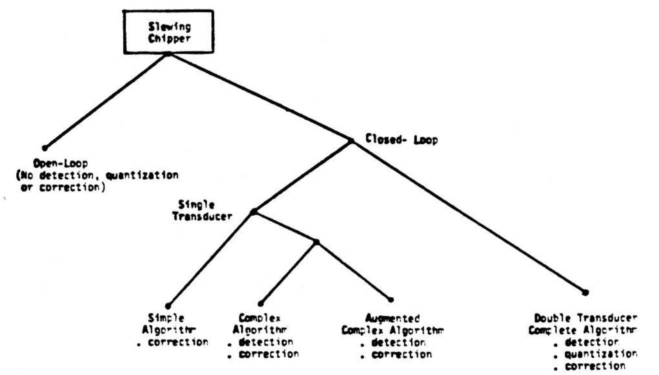

Figure 5 Relationship Between Chipper Positioning Strategies

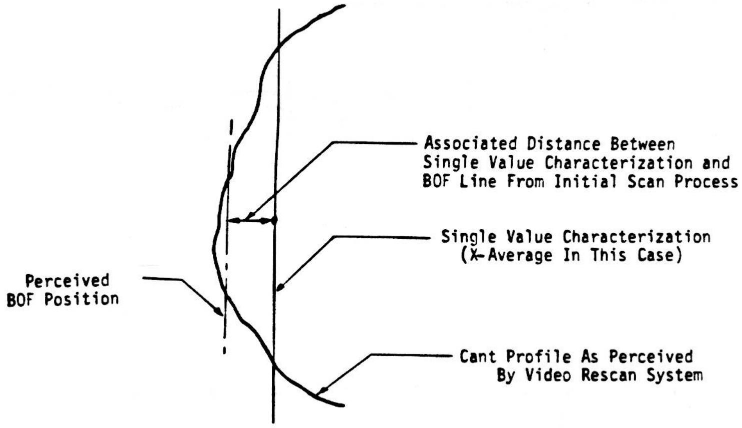

Figure 6 Recovering the Best Opening Face Position With a Rescan

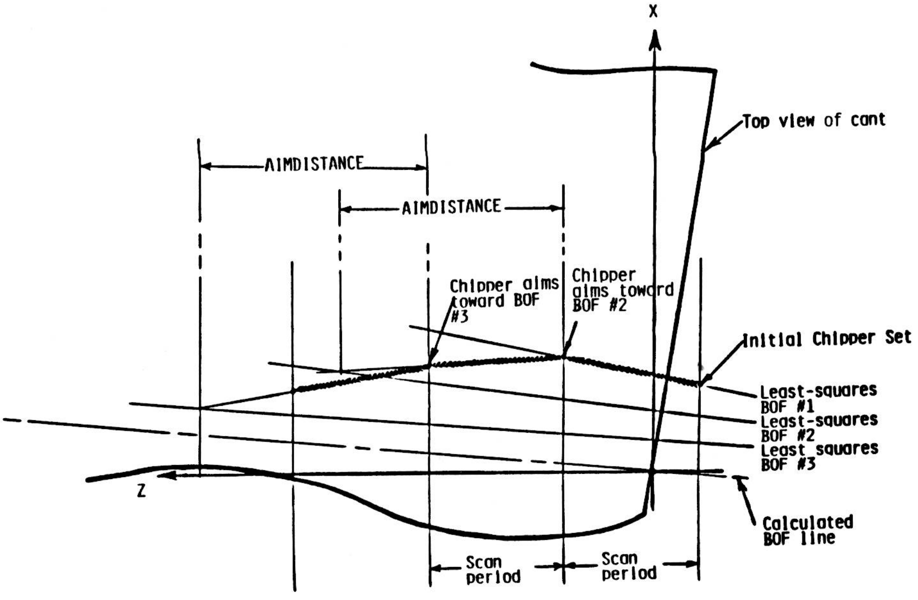

Figure 7 The AIMDISTANCE Strategy for Cant Coordinate Recovery

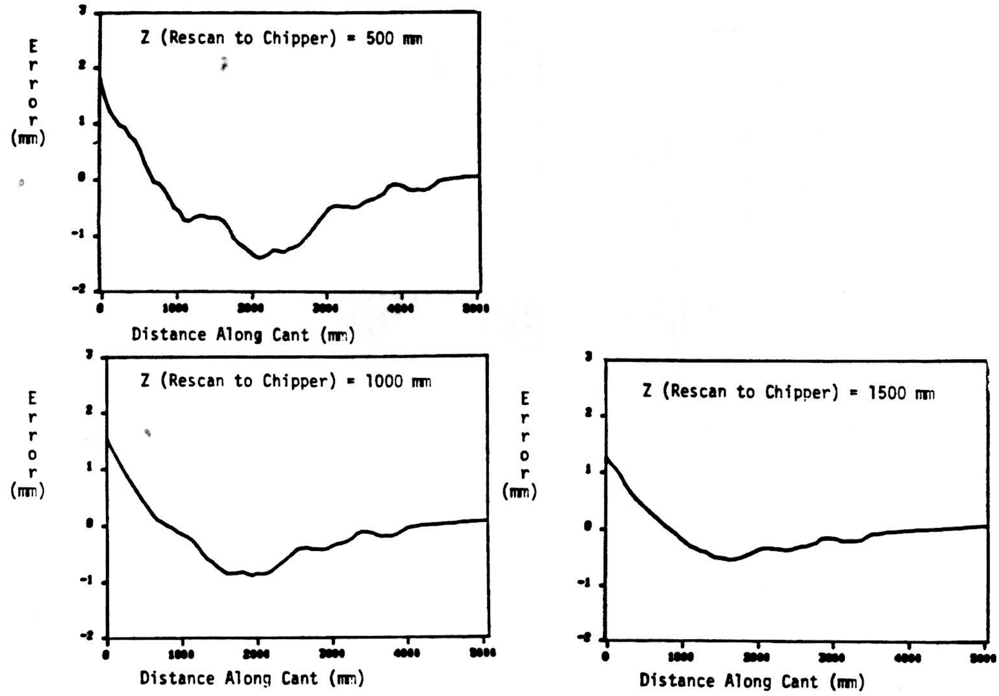

Figure 8 Effect of Varying the Distance Between Rescan and Chipper

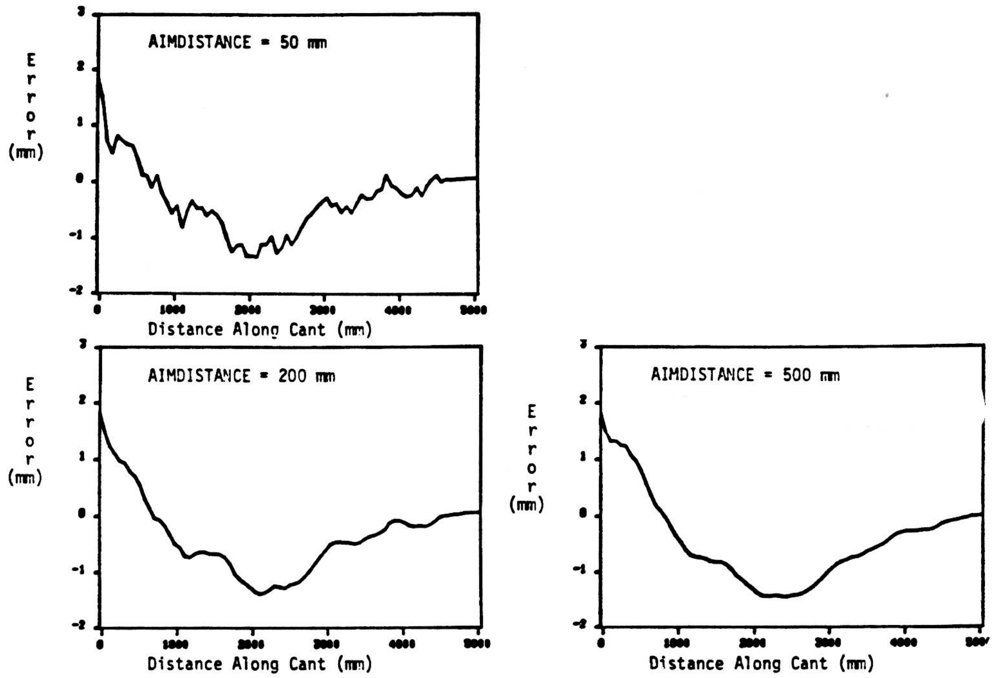

Figure 9 Effect of Varying the AIMDISTANCE