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Turbine Blade Image Processing System

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Abstract

A vision system has been developed at North Carolina State University to identify the orientation and three dimensional location of steam turbine blades that are stacked in an industrial A-frame cart. The system uses a controlled light source for structured illumination and a single camera to extract the information required by the image processing software to calculate the position and orientation of a turbine blade in real time.*

Background

The development of the image processing/robot vision system that is the subject of this paper was begun in February of 1982 at North Carolina State University in Raleigh, North Carolina. The research is sponsored by the Westinghouse facility in Winston-Salem, North Carolina, in response to their need to automate specific portions of their steam turbine blade manufacturing facility. This system has been designed to provide "vision" to a Cincinnati Milacron HT3 industrial robot so that it can reliably unload turbine blades into various machines from transportation carts within the plant. The facilities that have been available for this research include a DEC VAX 11/780, an IKONAS color display system, and a laboratory robot.

Introduction

This image processing system has been developed to provide "vision" to an industrial robot so that it would be able to unload steam turbine blades from an industrial cart. Vision capabilities were required for this robot because the turbine blades are stacked in a semi-random fashion on the A-frame carts that are used to transport the blades between manufacturing steps within the plant. The carts have partitions that keep the blades almost vertical and in relatively ordered piles, but the exact location of the edges of the topmost blade on the pile are not known. The three dimensional coordinates of these two edges are required by the robot; consequently, a vision system was needed to determine these coordinates and give them to the robot.

The turbine blades being considered exhibit specular characteristics. They are made of steel that has a smooth, brushed surface, and they vary in length from about 6 inches to 4 feet. Also, the curvature and degree of twist of individual blade types vary considerably.

The initial goal of this research project was to develop a reliable vision system to accomplish the practical goals of unloading turbine blades from a cart in real time. This problem is not an unfamiliar one. Our solution uses only a single camera in an effort to reduce the total system cost, memory requirements, and processing requirements while increasing the reliability and ruggedness of the system since its application is in an industrial environment.

A general description of the system that has been developed will be presented, along with the restrictions that are necessary for proper operation. Also, the geometrical relations that enable the use of a single camera to determine the three dimensional coordinates of a point in space will be described, and the image processing techniques that are used will be discussed. In addition, theoretical accuracy limits and preliminary, laboratory performance results of this system will be presented.

General system description

This system uses a procedure called structured illumination. In this procedure, a light source is located directly above the camera and projects a horizontal stripe of light onto the turbine blades that are in the pockets of a cart. The angle of projection (with respect to horizontal) must be known to a relatively high degree of accuracy, and the vertical separation between the light source and the camera must also be known accurately. Thus, a highly controlled light source is required.

*This research is sponsored by the Turbine Components Division, Westinghouse Corporation.

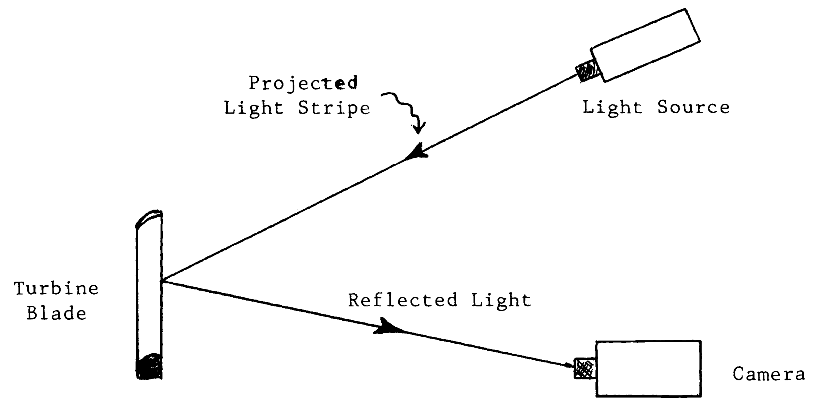
The light source that has been used for the development of this system is an inexpensive filmstrip projector that has been modified to project a horizontal stripe of light. The light stripe it projects is not very intense, and the measurement of the angle of projection does not yield a precise measure. This has resulted in problems when evaluating the system performance.

A single camera is used to extract the three dimensional position and orientation information about each turbine blade from one image. The controlled light source eliminates enough variables so that range information can be extracted from this frame of data; however, work is also being done with stereo images (two cameras) to provide a second mechanism for determining the three dimensional location of a blade.

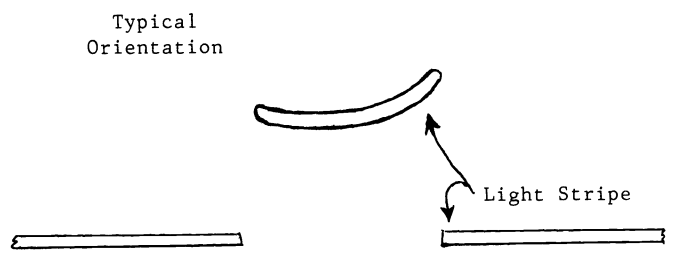
The cameras that are being used are DAGE.MTI 66 cameras, and they are of more than adequate quality for both the system development and the final system.

Principles of system operation

The key to the system is the controlled light source that is vertically offset from the position of the camera (see Fig. 1). The light stripe is projected onto the blades, and from the position of the camera, it appears that the light stripe consists of discontinuities and curves (see Fig. 2).

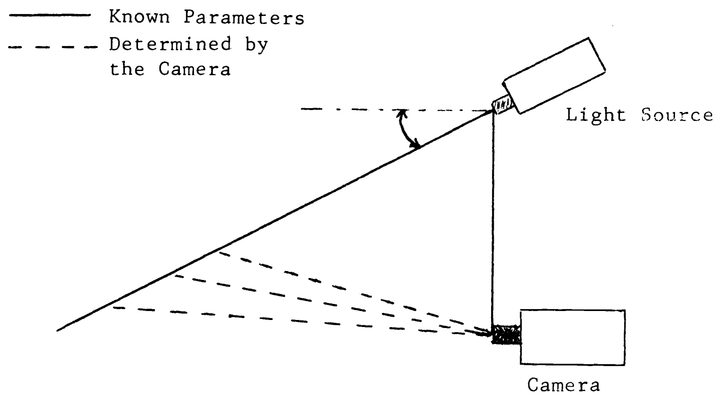


System Layout (Side View)
Figure 1.



Camera's View of a Single Blade
Figure 2.

An important concept to recognize is that the closest point of the turbine blade to the camera will appear as the highest point of light as viewed by the camera. With this knowledge, the range (with respect to the camera) of a point on the turbine blade can be calculated because the angle of projection of the light stripe is known, and the separation of the light source and the camera is known. Thus, the image in the camera completes a "range triangle" to the turbine blade (see Fig. 3).



Range Triangle
Figure 3.

A restriction that has been placed on the stacking of the turbine blades is that they must be stacked in the A-frame cart with the concave side facing the camera. With this restriction, the closest point of a turbine blade to the camera will always be an edge of the blade. This knowledge is useful in determining the orientation of the blade and in locating both the edges of the blade.

Image processing software

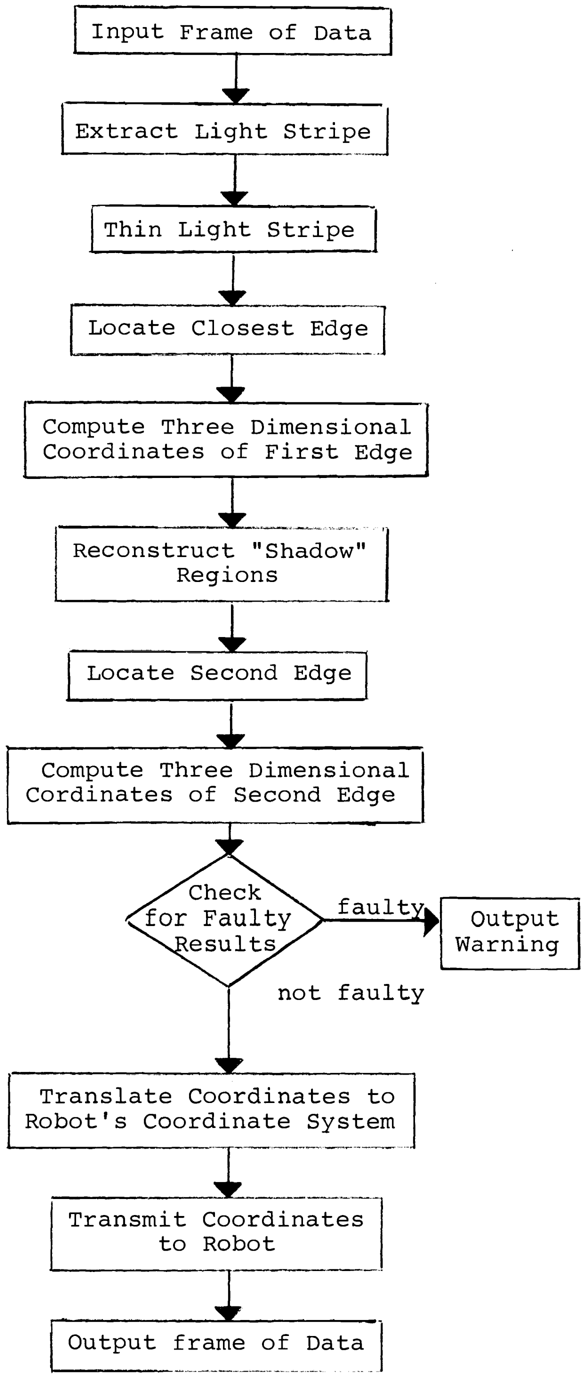
The image processing software that has been developed is written in PASCAL and is executed on a DIGITAL VAX 11/780. This software has been developed in a modular form so that specific operations and calculations are performed in procedures that are external to the main program. This was done to simplify the development process and so that it would be easier to migrate the software to an industrial system within the manufacturing facility that is different from the existing laboratory system.

The program begins by storing a frame (picture) of data from the camera in the memory of the computer. A dynamic threshold routine separates the light stripe from the background of the frame, and the background is eliminated. Then, the image of the light stripe is thinned down to a single pixel width line. The closest edge of the top blade is found next, and the range to this point is calculated using simple trigonometric relationships derived from the range triangle.

Apparent "shadows" are sometimes present on the surface of the blade, so a linear interpolation reconstruction routine is used to estimate the location of the projected stripe image in these blank areas. This facilitates locating the second edge of the top blade and the approximation of the blade curvature. At this point in the program, the second edge is located by beginning at the known edge and searching in both directions along the thinned, reconstructed light stripe until the discontinuity that corresponds to the second edge of the top blade is found (refer to Fig. 2). The range to this edge is calculated, and the curvature of the blade is approximated by fitting a second order quadratic curve between these two edges. This curve is used to check if the blade is properly stacked and to give some indication of the accuracy of the calculated results.

If the results appear to be valid, the three dimensional coordinates of both of the top blade's edges are translated from the camera's coordinate system to the coordinate system of the robot and sent (in hexidecimal form) serially to the robot. These coordinates are all that is necessary for the robot to move to the "approach" position in front of the blade because of software that is present in the processors of the robot that calculate the appropriate approach vector. The "approach" position is on the perpendicular bisector eight centimenters from the intersection of that bisector and the line segment between the two edges of the blade.

Finally, the modified frame of data is output to either the color display or a data file for human examination.



Flow chart of image processing software

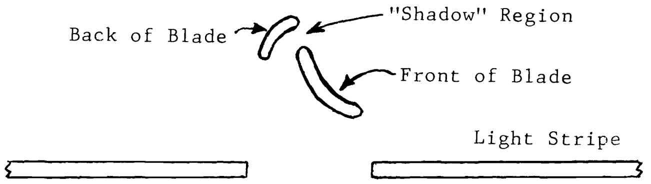
One of the main goals of the program is to never give incorrect results and to recognize if it is unable to produce reliable results; consequently, there are several error checks built into the program. One check identifies if the blade is in a highly twisted orientation (as viewed by the camera), even though under such conditions it is sometimes possible to compute all the desired results. Another check recognizes if the blade is incorrectly stacked, violating the basic restriction of the program, and outputs an appropriate warning because the calculated data will most likely be faulty. In addition, the program will check the validity of the second edge's location, or it will report if it cannot find the second edge, and it will identify which edge it was looking for. These error checks are the result of the software testing and fine tuning that have been done to increase the system's performance.

Problems encountered

Problems that have been encountered with the development of this system include light source control, measurement of the system parameters, light source intensity, inaccurate thresholding, ambient light, "shadows" on the blade, and camera blooming.

Several significant problems have centered around the crude light stripe projectors that have been used to date. Controlling the angle of projection of the light stripe, for example, has proven to be quite difficult. Instead of setting the angle of projection to a specific, desired angle, the light stripe must be directed to an acceptable angle, and then that angle must be carefully measured. Unfortunately, measuring the system parameters that are related to the light source is somewhat difficult; however, by repeated measurements and cross checking the range calculations with known results, the system parameters have been measured accurately. Another problem that is associated with the projector is the low intensity of the projected light stripe. This has magnified the problems of reducing the ambient light and performing thresholding operations that extract the light stripe. A more intense light source may essentially eliminate these problems, and a more highly controlled light source will be necessary for a practical, industrial system.

Situations where "shadows" seem to appear on the blade have also caused problems with the processing software. These apparent "shadows" may in fact be due to two phenomena, the specular reflectivity of the blade, and true shadowing. In the former case, the normal to the blade surface can be oriented in such a way that virtually all light is reflected away from the camera, thereby producing a dark area in the image. A solution that has been developed to help compensate for these shadows is a routine that reconstructs the missing data by linear interpolation in these blank regions. Another suggestion that has been proposed is to increase the intensity of the light source and simultaneously reduce ambient light in the industrial environment by filtering out the sodium vapor light that is used in the Westinghouse facility. Tests with polarizing filters are also being conducted. In addition, work is being done to experiment with different types of dynamic threshold routines to further improve system performance; however, the existing routine seems to be satisfactory, especially if better light sources are obtained. The blooming problem will most likely be minimized with improved ambient light control and better light sources.



Highly Twisted Single Blade
Figure 5

Three-dimensional accuracy

The absolute accuracy of the three dimensional range calculations using this single camera method is entirely dependent upon the accuracy of the measurement of the light/camera separation and the projection angle of the light stripe. The errors are linearly related to the light/camera separation error, but are exponentially related to the error in the measure of the projection angle. Assuming that the light source can have its angle of projection and separation from the camera accurately measured, the range calculations can realistically obtain millimeter accuracy. Observed results support this conclusion. With the crude laboratory measurement devices that have been used (a meter stick and flexible tape measure), the range calculations have consistently yielded results that are accurate to less than one centimeter.

Testing results

The goals of the testing process have been to fine tune the system's performance, to identify the range of acceptable blade orientations for successful system operation, to adapt the software to gracefully handle unacceptable conditions, and to determine the overall performance of the system. The performance of the sytem with a single blade in the A-frame pocket has been extensively tested and the results are quite good. Failures have occurred less than 3% of the time, where a failure is either incorrect results or an incorrectly detected error. Testing with multiple blades in a pocket has yielded similar results, assuming the basic initial restrictions for blade stacking are met.

Continuing research

Research is continuing on the development of this vision system for steam turbine blades in an effort to reduce some of the stacking restrictions that are present with the existing procedure. Also, experiments are being performed to further improve the overall system performance and to try and solve some of the problems previously mentioned that tend to hamper this performance. In particular, a project is underway which will eliminate the need for structured lighting. Work has just recently begun on adapting and migrating this system to the industrial environment of the Westinghouse turbine blade facility.

Summary

The vision system that has been developed at North Carolina State University for Westinghouse uses a single camera and a controlled light source for structured illumination. The image processing software gives the three dimensional location and orientation information about the top turbine blade in a pocket of an industrial A-frame cart, if the blades are stacked relatively neatly with the concave side facing the camera. It also checks the accuracy of its results and gives warnings if the blades are improperly stacked. The system yields results that are accurate and quite satisfactory for the control of an industrial robot.