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INTEGRATING A VISION SYSTEM WITH A COORDINATE MEASURING MACHINE TO AUTOMATE THE DATUM ALIGNMENT PROCESS

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ABSTRACT

Inspection is an important stage in the manufacturing process of machined parts. Coordinate measuring machines (CMM) have become more automatic, programmable, and capable of fulfilling the growing demands of inspection. However, fixturing (datum alignment) of parts is still done manually, consuming valuable inspection time. In this paper, we describe an automated datum alignment technique which integrates a vision system with the CMM to avoid part fixturing. The rough position of the part is estimated through image analysis. This initial reference frame drives the CMM through an automatic datum alignment procedure, thereby automatically establishing the reference frame without the use of fixtures. This technique has been demonstrated for two and a half dimensional (2.5D) machined parts with well-defined features that exhibit a stable position on a flat table.

INTRODUCTION

Inspection is an important stage in the manufacturing process of machined parts. It is the process of checking products against their models based on the established standards followed by industry. The aim of inspection is to eliminate defective and non-conforming products, thus maintaining high quality. The increased efficiency and automation of machine tools has created the need for faster and more flexible means of measuring in order to keep up with the ever increasing rate of production. Industry has been experiencing rapidly increasing demands for reduced production time and improved product quality, particularly in relation to the production of complex components such as turbine blades and car engine parts. This trend has resulted in the need to perform accurate and rapid dimensional measurements on complex shapes and to integrate inspection with the design and manufacturing processes. The general inspection methodology is summarized in Figure 1.

1. Define base coordinate system and inspection path based on part CAD model.
2. Create fixturing hardware specific to part and affix hardware to the CMM workspace.
3. For each part:
   A. Manually affix part to fixture
   B. Run CMM program to sense actual part coordinate frame
   C. Run inspection algorithm

Figure 1: CMM Inspection Methodology

Coordinate measuring machines (CMMs) are widely used in most manufacturing plants as one of the most powerful metrological instrument [3]. Typical applications of CMMs include part measurement, inspection of manufactured parts, reverse engineering, and statistical quality control. CMMs are very accurate but have some important limitations such as: the need for mechanical fixturing, low measurement speed, and the need to be reprogrammed as new parts are inspected. A fixture is a mechanical device which holds the part to prevent any movement during inspection and ensures the each part maintains the same position during future inspections. Once the part is fixtured on the table, the reference frame of the part is set manually to match the computer aided design (CAD) model reference frame. Fixturing and datum alignment (Steps 3.A and 3.B in Figure 1) may consume a majority of the total inspection time depending on the complexity of the fixtures [9].

Non-contact sensors (such as laser and vision based systems) can increase the inspection speed saving valuable inspection time. However, their measuring accuracy is relatively low when compared to contact methods (touch-probe CMMs). CMMs have a measuring precision around 1µm while that of laser scanners and vision systems are approximately 10µm and 100 µm respectively. This is the major drawback for using non-contact measuring techniques, as usually quality cannot be compromised to speed up inspection. Additionally non-contact sensors are not suited for sensing deep concavities that obstruct the line of site of these instruments [5] (e.g., features that cannot be seen from any position of the camera (or

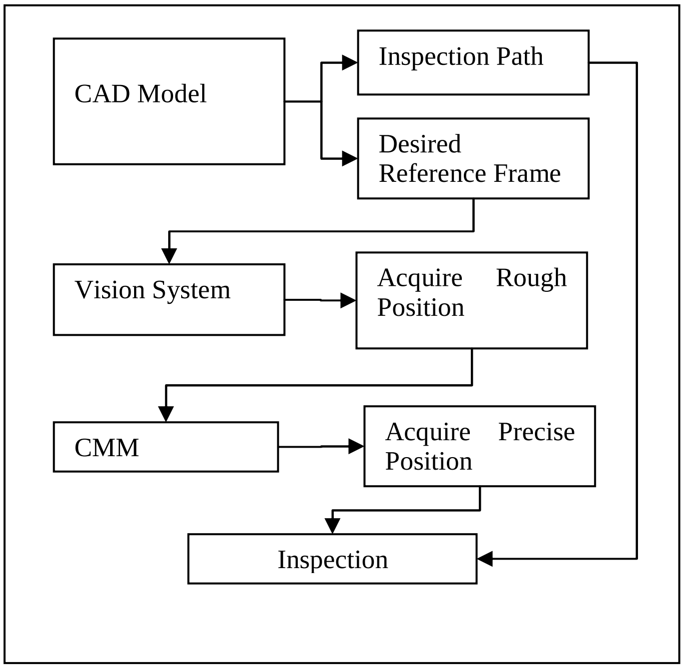


Figure 3: Integrating the CMM and Vision System

cameras), such as bends in bores through an object). Further, features smaller than the resolution of the vision system, such as small holes and screw threads, cannot be inspected. Typically a CMM probe is capable of sampling at a much higher resolution than the size of a camera pixel and can sense the inside of concave regions.

The advantages of vision systems over contact sensors include flexibility, speed, and cost. We suggest that by adding a low-cost vision system to a high-cost CMM, we can harness some of the speed of the vision system without sacrificing the accuracy of the touch probe. In this research, we demonstrate a vision-based system used to determine the position and orientation of each part before inspection takes place, thus eliminating the need for a physical fixture

Previous research has suggested the integration of contact and non-contact methods, but not for the specific purpose of removing the manual fixturing stage. Yoshimi et al [6] described a calibrated and an uncalibrated method for integrating a vision system with a CMM but do not deal with methods to avoid the use of fixtures or virtual fixturing. In their work, a vision system is used to direct the movement of CMM with millimeter precision while the touch probes are used to recover sub-micron displacement information. Nashman et al [8] described a real time hierarchical system that combines data from vision and touch sensors to simplify and improve the operation of a CMM used for dimensional inspection tasks. In their system, the vision component provides a position estimate of the features of interest while moving the touch probe. Nashman et al [7] described the integration of vision and touch sensors in a CMM controller used for dimensional inspection tasks. In all these papers, the vision system is used to dynamically track the CMM probe. In our research, we use the vision system to provide the rough position of the part's reference frame, require the CMM to refine this positional

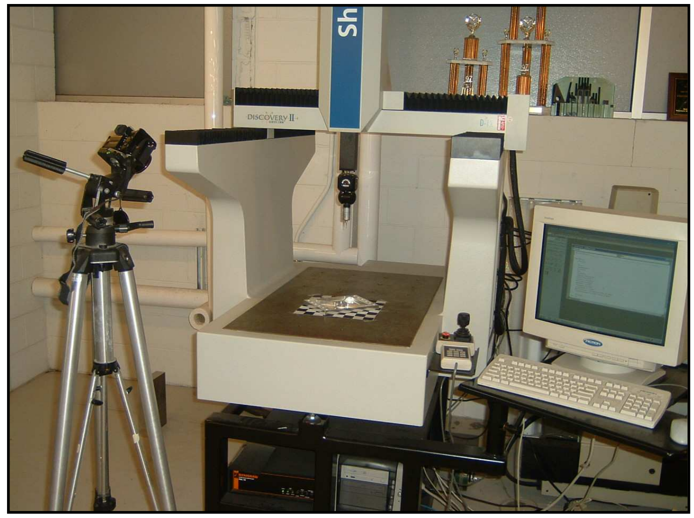


Figure 2: Camera Setup in Relation to the CMM

information, and then allow the automatic inspection process to proceed.

There are certain simplifying assumptions utilized by our research. First, the object domain is restricted to two-and-a-half dimensional (2.5D) parts. Second, the part must be positioned in the center of the CMM workspace with an orientation between 0 to 90 degrees. Such requirements, while not essential, allow for fast and efficient implementations of the image analysis without undue burdens being placed on the engineer which would require increased inspection time.

The process (Figure 3) thus becomes, 1) evaluate the model to choose a coordinate system and inspection path, 2) generate a part program to drive the CMM in acquiring the true position of the part, 3) place the part in the CMM workspace, 4) capture an image of the part to provide an initial position estimate, 5) drive the CMM to refine this estimate into the actual part position, and 6) execute the generic inspection routine. Steps one and two are only executed once per part. Steps three through six are repeated for each part. The traditional inspection routine would replace step 3 with a manual fixturing of the part. It is at this step that we feel the greatest speedup can be realized.

INSTRUMENTATION AND INSPECTION PATH GENERATION

The general inspection methodology is shown in Figure 1. The CMM used in this research was a Sheffield Discovery II series. The inspection paths were generated using CadPath [2] software in Measuremax [1]. Measuremax uses a Visual Basic interface and special commands called MLB commands to program the CMM. CadPath is an automatic inspection path generator based on CAD model for CMM path planning. Simulation of the inspection path can be viewed before running the actual inspection process. Path planning software is a common component associated with CMMs application software.

Every part must have a reference frame associated with it for the inspection routine. This reference frame is almost always defined in terms of part features (e.g., planar surfaces,

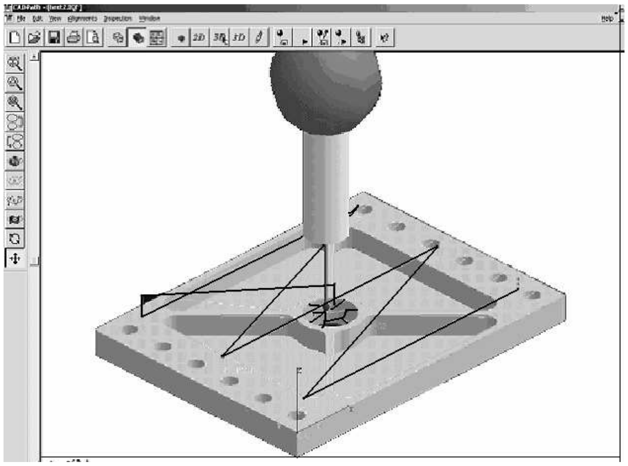


Figure 5: Inspection Path Planning and Anchor Coordinate System in CadPath

holes, etc.). These features are predetermined by the engineer[1]. Once the reference frame and features of interest (those to be inspected) are identified, the inspection path (see Figure 5) is generated automatically. This step (#1 in the inspection methodology) is common to both fixtured and non-fixtured inspection algorithms.

The vision system used in our research comprises of a digital camera and a personal computer. A Nikon digital camera is used to take image of parts. This camera is an off the shelf model without any special lens component. Matlab is used for image analysis and CMM path planning. The system can be seen in Figure 2.

The parts used in the research are confined to two and a half dimensions and are made of aluminum. Initially, a test plate was machined with well defined holes and pockets to use as a demonstration part. Then, a set of parts from the University of Utah 2004 student competition Formula SAE racecar were tested. These parts include a gear box cover plate, a differential gear assembly end plate, and a shock linkage.

SYSTEM GOALS

The goal of this research is to integrate the high precision measurement of a CMM and the time saving feature of a vision system in order to increase overall part inspection speeds. It should be clear that any change to the current inspection methodology must be effective, save time, and provide high precision results. In a typical inspection scenario, the part is manually attached to the CMM workspace via a fixturing device, and then the reference frame of the part to be inspected is manually located by the CMM operator. We remove the human from this operation, replacing him or her with a vision system which locates the rough position and orientation of the part on the CMM table. This saves valuable setup time and

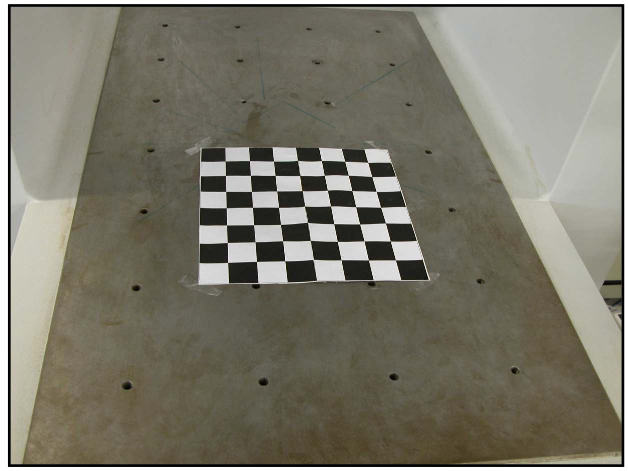


Figure 4: CMM Workspace Registration Target

avoids the use of fixtures. The rough position and orientation of the part provided by the vision system is used as an initial reference frame to drive the CMM. The CMM then senses the required reference features, calculates the true reference frame of the part, and inspects the part following the same inspection path calculated and stored a priori by the user.

EFFECTIVENESS AND PRECISION

In order to remove the fixturing step, several factors must be taken into consideration. 1) The rough position and orientation of the part obtained from the vision system must be accurate enough for the CMM to locate the part on the table. 2) The part must be shown to not move during the inspection process. 3) The speed of the method must be significantly faster than the manual process.

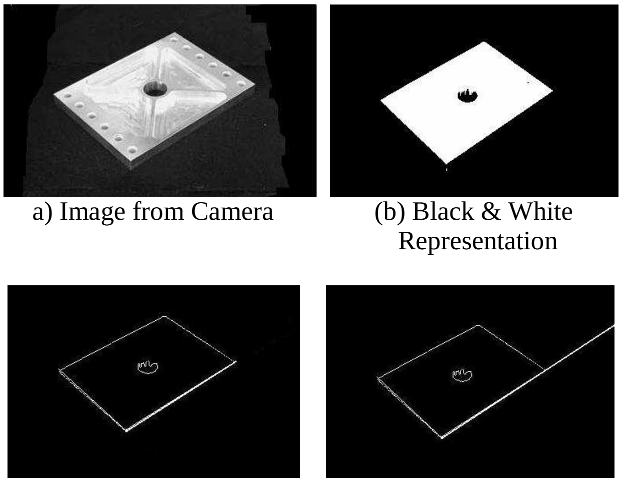
Factor one, position acquisition, is discussed in the following section, where we show the ability to automatically drive the CMM via a vision system. Factor two involves the stability of unfixtured parts. In most cases, the parts are significantly massive that the negligible force with which the probe makes contact results in no displacement of the part. If required, stability can be further increased by the simple mechanism of using clay to stabilize and immobilize the part. Factor 3, increased system throughput, is achieved by avoiding the use of fixture. Fixturing the part and setting reference frame consume majority of the inspection time.

POSE ESTIMATION

Pose estimation is the process of defining the transformation needed to map an object from its current coordinate system based on sensory data into the coordinate system of the CAD model [10]. More generally, it is the process of finding the position and orientation of the part in space. Systems need the ability to determine the pose of objects in their environment to be able to reliably and intelligently interact with them. In this work, the purpose of the vision system is to estimate the three-dimensional position and orientation of the part based on the image of the part.

The pose is obtained by analyzing the image of the part to determine the rough position and orientation of the part on the

[1] It should be noted that future work toward automatic methods should include the ability to hypothesize appropriate coordinate frames directly from the CAD model with little or no human interaction.



a) Image from Camera (b) Black & White Representation

(c) Edge Extraction (d) Orientation

Figure 6: Vision Method

CMM table. This position is given as the initial rough reference frame that provides the CMM reference acquisition program enough information to find the true location of the part. The pose is determined by calculating a transformation matrix, which maps 2D pixels on the image to the real world-coordinates in terms of the CMM workspace.

The digital camera has been mounted[2] on a tripod facing the CMM table as shown in Figure 2. The CMM workspace has a registration target as shown in Figure 4. These targets facilitate the camera calibration and pose estimation process. The actual pose estimation is made using the transformation detailed in the next section.

IMAGE TO WORLD COORDINATE TRANSFORMATION

The transformation matrix is calculated to map the pixel position of the part in the image to the 3D positional coordinates of the part on the CMM table. For this purpose, a registration target (checkerboard) was placed on the CMM table as shown in Figure 4. The transformation matrix is obtained by mapping the location of checker board squares on the CMM table to their corresponding pixel position in the image. The transformation matrix obtained is considered for the position calculation.

N = Number of pixels considered.
$T_{[3x3]}$ = Transformation matrix.
$P1_{[Nx3]}$ = Pixel position of squares in the image.
$P2_{[Nx3]}$ = Corresponding position of squares on the CMM table
$P1^T$ = Transpose of P1
$T = inverse([P1^T * P1]) * [P1^T * P2]$

Once the transformation matrix is calculated, the position of the part on the CMM table can be determined from the pixel position in the image.

$A_{[1x3]}$ = Pixel position in the image.
$B_{[1x3]}$ =Corresponding position on the CMM table
$B = A*T$

The B matrix gives the location (X, Y) of the corresponding pixel on the CMM table.

ORIENTATION ESTIMATION

The next step after finding the basis point of the part is calculating the orientation. The test plate used to validate our algorithms is shown in Figure 6a. It is a two-and-a-half dimensional (2.5D) machined plate with well defined holes and pockets. The orientation of the part is calculated based on recovered features of the part, such as linear edges and holes. For our purposes, the part is photographed versus the black background of the CMM workspace. This image is histogrammed and thresholded to achieve a well-defined edges set of ‘part pixels’ (Figure 6b). Edge detection [11] is performed on the image to extract the boundary edges (Figure 6c). Finally the edges are analyzed to determine the orientation of the part (Figure 6d).

Many line extraction algorithms exist. The algorithm implemented for this research identifies all the major lines in the image using a Monte Carlo technique and then sorts these lines based on their pixel count. For more complicated parts, factors such as line length could be considered or more in depth pattern matching could be utilized. Once the line of interest is successfully located, the orientation of the part is obtained by using the transformation matrix. This technique is adequate because the inspecting engineer has been required to place the part in a reasonable manner.

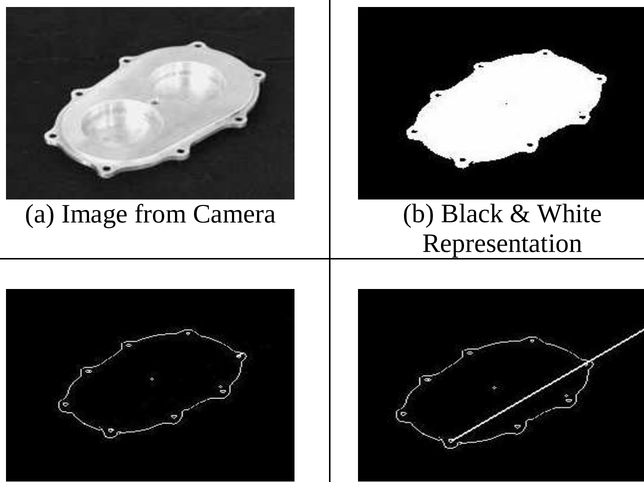
It should be pointed out that for certain parts, namely those with strong symmetries, it is possible for the system to misidentify the primary orientating feature. In such cases user input is currently utilized. Future work would utilize more advanced pattern matching algorithms.

Stochastic Line Extraction Algorithm:

1. The image is thresholded to separate the part from the back ground (see Figure 6b) and a list of pixels is created from the image.
2. A stochastic method is employed which randomly selects pairs of pixels[3], creates a line through them, and counts the number of pixels on this line. Any line that contains a significant number of pixels is set aside for consideration and the pixels removed from the sample set.

[2] Future versions of this system should incorporate the camera mounted directly to the CMM. This would provide a more compact/integrated solution and allow for multiple images to be taken from different vantage points thus handling more complex parts.

[3] Given that the main edge of interest will contain a significant (greater than 10%) number of pixels, it can be shown that statistically we only need to sample the pixel list a set number of times in order to have a 99.999% surety of finding the desired edge. If P is the probability of choosing two pixels on the desired feature and N is the number of random samples we take, then by solving $(1-P^2)^N < delta$, where delta is the desired accuracy, we can determine N. In our research we sampled the data 600 times.



(a) Image from Camera — (b) Black & White Representation — (c) Edge Extraction — (d) Orientation

Figure 7: Cover Plate

HOLE FINDING

For parts that do not have linear edges (e.g., Figure 7), the orientation is calculated by identifying the position of holes in the image. We employ the Hough transform [11] technique to extract small diameter circles from the image.

The positions of the holes found in the image are transformed to CMM workspace coordinates using the pre-computed transformation matrix. The orientation of the part is then computed based on a line between two specified hole features. This circle extraction technique has problems when applied to larger diameter holes as their silhouettes form ellipses. A straightforward solution to this problem is to mount the camera vertically above the CMM workspace or to implant a more robust ellipse finding routine [12]. This technique was successfully applied to the cover plate of a gear box as shown in Figure 7d.

FROM ROUGH COORDINATES TO ACTUAL COORDINATES

To accomplish the actual data alignment, two sets of information are necessary. One is the defining features of the model coordinate anchor frame (such as the corner shown in Figure 5). Both our system and a traditional system require the anchor coordinate frame. A traditional system would ask the inspection engineer to manually sense each defining component (in the case of Figure 5, the three intersecting planes) or manually create an automated CMM path program for use on each additional part beyond the first. For our system, a small software program is manually written defining how to sense each anchor feature based on the approximate location of the part. This programming takes less than thirty minutes (comparable to the traditional method) as programs from previous parts can be quickly modified for use on new parts. Further effort could automate this process entirely by creating a set of feature-sensing algorithms (e.g., plane sensing, hole sensing, line sensing, etc) which would be automatically compiled together based on the CAD model's reference-frame features.

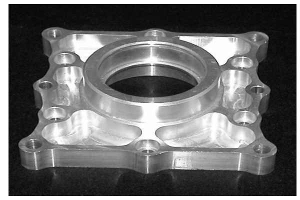


Figure 8: End Plate

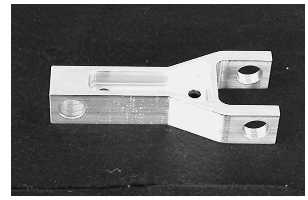


Figure 9: Lower Linkage

The second piece of information required for datum alignment is the rough position and orientation of the part. A traditional system provides the rough location of the part by using a physical fixture. Our method provides the rough location via a vision system. The vision system produces rough coordinates offset from the actual reference frame by some millimeters (based on the positional accuracy of the vision system). A fixtured part would be an order of magnitude more aligned, but still would require a sensing process as fixtures can contain errors larger than the desired tolerances (e.g., dust particles could be wedged between the fixture and the part). To compensate for the vision system inaccuracies, the alignment program provides the CMM with clearance and overdrive distances. We have found two centimeters sufficient to ensure collision free sensing of the part (additional research would be required for more complex parts where probe/part collision detection is necessary). This clearance distance ensures that the probe approaches the feature at the specified distance away from the rough position. Overdrive distance is the distance through which probe continues its path till contact with the feature is established.

RESULTS

An integrated CMM/vision system was successfully achieved. The rough position and orientation of the part , obtained by analyzing the image, have been shown to be accurate enough to provide an initial reference frame. The CMM was successfully programmed to locate the reference features based on the rough position of the part, and hence, to determine the new reference frame automatically. Finally the part was successfully inspected.

The orientation of the part was calculated from the slope of the line obtained from the image. The angular accuracy (orientation) of the test plate ranged from 0-4 degrees (see Table 1). The positional accuracy obtained from the image analysis ranged from 0-4 mm for both X-coordinates and Y-coordinates. The results are within the CMM probe scan limits. The CMM probe senses the position and orientation of the part based on the results obtained from the vision system.

The algorithm was applied to various test parts showing linear and non-linear features and symmetric properties (see Figure 6, Figure 7, Figure 8, and Figure 9). For each part an inspection path was preplanned, and the anchoring reference features where pre-determined. Each part was manually placed in the CMM workspace, an image was taken, the part was successfully analyzed, including position and orientation, and the part inspection routine was carried out. The results for end plate and link are shown in Table 2 and 3 respectively.

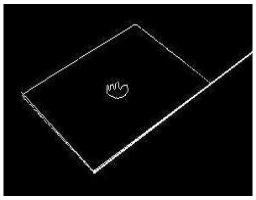
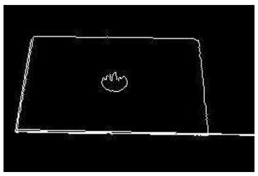
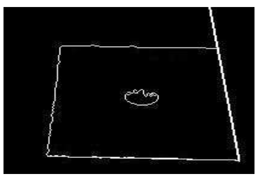
Orientation of Plate	CMM Table (deg)	Vision System (deg)	Positional Accuracy	
			X(mm)	Y(mm)
	0	1	3.82	1.9
	45	41	3.82	1.9
	90	88	3.82	1.9

Table 1:Angular and Positional Accuracy of Plate

CONCLUSION

In many inspection systems, the process that consumes the most time has been identified as that of part fixturing and datum alignment. The main objective of this research was to show a method that avoids the use of fixtures and thus save valuable inspection time. We have incorporated a vision system along side a CMM to automate the datum alignment process. The image of the part on the CMM table, obtained from the digital camera, is analyzed and a rough position of the part is calculated as an initial reference frame. Additionally, based on the anchoring geometry of the model coordinate system, a program is produced to guide the CMM in sensing the actual position of the part given the initial, vision based, reference frame as an input. Finally, the probe inspects the features of the part according to the pre-generated inspection path.

In any automated system, the degree of automation achieved is very important. In our system, the engineer does not need to fixture each part to the workspace, but can merely place the part at a reasonable location on the CMM bed. By avoiding fixturing the part and further, not having to manually find the part reference frame, valuable inspection time is saved during each inspection. Additional time is saved by not having to design and manufacture the fixture. In general, it is estimated to take at least several hours to set up a modular fixture and, as a minimum, several days to manufacture a custom fixture. Once the fixture is created and set up, it would take from 2 to 10 minutes to manually set up and align each part.

The automated datum alignment technique developed has been shown to be effective for two and a half dimensional (2.5D) machined parts with well-defined features.

ACKNOWLEGEMENTS

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[12] Harding, K., “Randomized Hough Transform: Better Ellipse Detection,” IEEE Region 10 Annual International Conference, Proceedings/TENCON, v 1, p 409-414 1996.

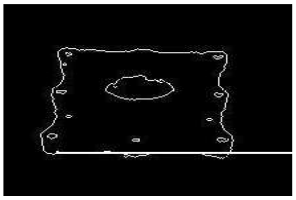
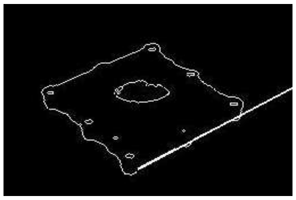
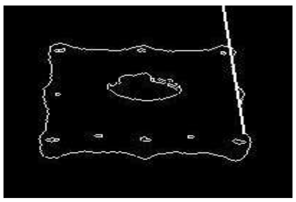
Orientation of End Plate	CMM Table (deg)	Vision System (deg)	Positional Accuracy	
			X(mm)	Y(mm)
	0	2	3.82	1.9
	45	42	3.82	1.9
	90	87	3.82	1.9

Table 2: Angular and Positional Accuracy – End Plate

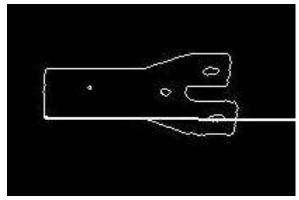
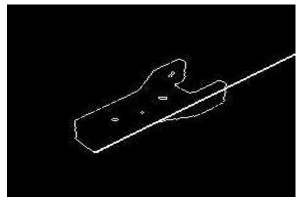
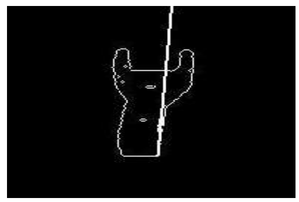
Orientation of Link	CMM Table (deg)	Vision System (deg)	Positional Accuracy	
			X(mm)	Y(mm)
	0	1	3.82	1.9
	45	41	3.82	1.9
	90	88	3.82	1.9

Table 3: Angular and Positional Accuracy – Lower Linkage