A Computer-Aided Inspection Methodology for Mechanical Parts based on Machine Vision

Palkush Rai Chawla and Sankha Deb

Department of Mechanical Engineering,
Indian Institute of Technology Kharagpur, Kharagpur-721302, India.
Email: sankha.deb@mech.iitkgp.ernet.in

Abstract :- With growing demands to minimize the requirement for manual intervention and improve the productivity and ensure high product quality, automated inspection has become indispensable to manufacturing facilities. The methodology described in this paper is an attempt for automating inspection in manufacturing by use of machine vision system. This is achieved by using image processing techniques to extract geometric information from images of the mechanical components, and then interpreting them as features to describe the component. This feature description is stored as a coded matrix which serves not only as an identifier but also as a group technology code to classify parts into families. Presently the methodology works on parts with simple features such as holes, steps, tapers, etc. and is found to give promising results.

Keywords: *Automated Inspection, Machine Vision, Parts Classification, Part Identification*

1. INTRODUCTION

In modern manufacturing industries, growing demands to minimize manual intervention, improve productivity and ensure high product quality have made automated inspection indispensable. Traditionally, manual inspection is carried out by visual verification with skilled personnel and customized metrology equipment that may require extensive manual labour. Even CMMs prove to be capital intensive for inspection where firstly, such high level of accuracy may not be required, secondly, speedy inspection process is needed, or thirdly, non-contact inspection is required. Hence, a machine vision based inspection system can prove to be cost efficient and fast. Machine vision techniques had been extensively used in manufacturing industry for various tasks like defect detection [1,2], dimension and tolerance checks[3], process control [4,5], robot guidance [6], etc. In these applications, object identification is generally achieved by matching key points on image of the object under inspection with those on a template image or a CAD model by application of statistical algorithms [7] or knowledge based systems [8,9]. However, these methods are computationally expensive and prove to be successful when object at hand has complex shape and intricate features. However, for simpler applications as in case of inspection of mechanical parts, instead of extracting key points, we propose to extract simple geometric features of the part, and encode them into a coded descriptor. This coded descriptor not only serves as a unique identifier of the part, but also as a basis for classification of parts into part families for application of Group Technology. Since the coded descriptor instead of images of parts is used, this method is expected to be faster and computationally more efficient.

2. PROPOSED METHODOLOGY FOR INSPECTION

We have developed an algorithm which analyses images of parts in different views to extract various geometric features like lines, circles, etc. and co-relate data from the 3 views to interpret them as machining features like holes, steps, taper, etc. This information is then encoded in a matrix which serves as the descriptor for identifying the part as a member of a part family, along with a Dimension array consisting of dimensions of features in order to calculate dimensional deviations. Finally, it has been implemented to inspect various mechanical parts.

2.1 Part Presentation and Scene Preparation

As for part presentation, crucial factors are part motion, positioning tolerances, and no. of parts in view. We consider parts and camera to be stationary relative to each other. Positioning tolerances are measured by calibrating the scene each time an image is taken by the use of a calibration artefact having standard dimensions. Also at present, methodology described uses only single part per view, but it can be extended to multiple parts in view. Major aspects of scene preparation include choice of camera, illumination and background. For this work, we use Canon EOS 1100D Digital SLR camera, with resolution 12.2 megapixels, and a kit lens with AF 18-55 mm compatibility. Photographs are taken under uniform strobe illumination using Flash Trigger. Background is a high contrast, matte-finish paper (White/Black) which is non-reflecting and can diffuse the incoming light, at the same time providing high contrast for edge detection.

2.2 IMAGE PROCESSING

Image processing steps are as follows.

2.2.1 Pre-Processing

Pre-processing includes preparing the image for analysis. Since subsequent steps depend heavily on pixel information of the image, it is necessary to remove noise from image data. To do this, image data is converted into simple binary form where 1 indicates presence of object, and 0 indicates absence. For removing graininess of image, Median Filter smoothening is used which removes salt and pepper noise from the image while preserving the edges. For noise removal, all connected pixels which are less than a threshold area are removed. In the final step all open contours are closed in order to develop a connected boundary of the object.

2.2.2 Feature Localization

In order to find features on the part, determine its dimensions and form, the part needs to be localized in the acquired image for which feature localization techniques are used. These include image segmentation using MATLAB's inbuilt Moore's neighbourhood tracing algorithm [10], by which we obtain the bounding box of various segments (also known as blobs) in the image. We then threshold these segments based on area threshold to eliminate unwanted blobs, in order to obtain bounding box of the part under examination.

2.2.3 Feature Extraction

In order to extract features of the part, it is put under visual inspection in 3 orientations, i.e. Top, Bottom, and Side Views, where Side View contains the rotational axis of symmetry, and top and bottom views are perpendicular to the rotational axis in both directions. Utilizing these 3 views enables us to examine the part from 2 directions, thus enabling measurement of dimensions as well as extraction of 2D and 2.5D features. For a part which does not have symmetry about any of the 3 orthogonal axes, a third view will have to be examined for complete part information.

2.2.3.1 Analysis of Top View

Using Top view of the part under inspection, we determine whether it is rotational/non-rotational, if it has holes, if holes are aligned in a pitch circle, etc. Once existence of these features is established, other parameters can be inspected e.g. once the part is established as rotational, its outer diameter can be measured against that of template, and its roundness can be checked.

Rotational/Non-Rotational Check

The following are steps to check if a part is rotational or non-rotational,

1. Find circles in segmented image of top view using Circular Hough Transform [11] function.
2. Eliminate circles with exceptionally low diameter as noise.
3. Sort circles in decreasing order of radii.
4. If circle with largest radius has diameter equal to length or width of bounding box, then part is rotational, else it is non-rotational.

Once the rotational nature of the part is found, centre of the largest circle is assigned as part centre and its radius as part radius.

Non-Rotational Shape Check

The following are the steps to examine a non-rotational part,

1. Find external boundary of part in top view using Sobel Edge detection Algorithm [12].
2. Find the lines in the external boundary of the part using Hough Transform.
3. Merge line segments which are part of the same line, by filling gaps between segments.
4. Eliminate the lines with length less than Min_Length.
5. No. of lines found determines shape of the part, as triangular, rectangle, pentagonal, etc.

Concentric Features Check

For the circles concentric with the part boundary, they may be a blind hole, stepped, or taper feature in the part. This can be confirmed only with the help of the side view of the part, so for the time being the concentric features are flagged as unknown rotational features.

Through/Blind Holes, Pitch Circle(s) Check

The following are the steps to check if a part has holes or not.

1. Find circles in segmented image of top view using Circular Hough Transform function.
2. Eliminate circles with exceptionally low diameter as noise.
3. If the centre of the circle is not equal to the part centre, then these features are holes.
4. If average Intensity Value (0 to 255) value of image inside the circle is equal to that of object Background, these are through holes present on the part, else these features are blind holes.
5. If number of holes ≥ 2, then the presence of a pitch circle is checked.

a. For no. of holes=2, draw a circle passing through centre of 2 holes, with their midpoint as centre.

b. For number of holes≥3, calculate distance of hole from part centre, and draw a circle passing through centre of 3 holes at same distance from part centre, and so on.

6. Determine the pitch circle centre and pitch circle diameter

2.2.3.2 Analysis of Bottom View

The analysis of Bottom view of the part is similar to analysis done in top view. It is used to find part features, which were hidden in top view. The bottom view can thus be used to discover concentric circular features, blind holes, through holes, and pitch circles as well. It can also be used to confirm presence and positioning of through holes in the part.

2.2.3.3 Analysis of Side View

The side view of the part is defined as one containing rotational axis in case of rotational parts, and longitudinal axis in case of non-rotational parts. This view is used to measure lengths of all the circular as well as non-circular features, and also to determine whether a circular feature detected in top view is an internal or external feature, if it is a taper or a stepped feature, and so on. The side view is taken such that Bottom View of the part becomes left view, and Top view becomes right view. This is important in determining whether part is stepped/tapered from one or both sides.

Align the image parallel to the Part axes

In order to inspect various linear and angular features, the part image needs to be aligned with the part itself. The following steps are followed to align the image with part's orthogonal axes.

1. Find the external boundary of the part by using Sobel Edge detection Algorithm.
2. Find the lines in the external boundary of the part using Hough Transform.
3. Find the line whose length = Part Diameter and calculate its slope as View Angle.
4. Rotate image clockwise by (View Angle- 90)

Define Rotational/Longitudinal Axis

The rotational/longitudinal axis of a part is defined as axis of rotational symmetry for rotational parts, and as central line for non-rotational part. In order to find the rotational Line following steps are followed.

1. In aligned side view of the part, find the bounding box again, by creating a rectangle between leftmost, rightmost, topmost, and bottommost points respectively.
2. The Width of the bounding box must be equal to Part Diameter, and the length of the bounding box is defined as Part Length.
3. Define a horizontal line dividing bounding box into 2 halves, this line is the Part Axis.

Left and Right Side part width

To identify features of the part as internal/external, we examine part width from left (bottom) side as well as right (top) side. Following are the steps to calculate the width.

1. Find the external boundary of the part by using Sobel Edge detection Algorithm.
2. Find the lines in the external boundary of the part using Hough Transform.
3. Find lines in the boundary of the part which are perpendicular to the Part Axis.
4. Find the length of the leftmost line segment from the above found lines, as Part Width Left
5. If Part Width Left = Part Diameter, part has internal or no features in bottom side
6. Similarly, If Part Width Right=Part Diameter, part has internal or no features on top side
7. Else, the features discovered in the top view are external features.

Find Concentric Features discovered in Top/Bottom View

In order to completely extract the features discovered in top/bottom view, they have to be matched with corresponding geometry in side view. This is done as follows.

1. Find the external boundary of the part by using Sobel Edge detection Algorithm.
2. Find the lines in the external boundary of the part using Hough Transform.
3. Find all the lines parallel to the Part Axis
4. Find the offset of the lines from the axis (+ve for above and –ve for below).
5. If offset distance of the line is equal to concentric feature radius measured in top view, the feature is external stepped.
6. Else, if no line with concentric feature radius is found, implies that the feature is a tapered feature.

Outlining for metrology

Next, we calculate the line segments which make up the boundary of the side view; this is done by using following steps.

1. Find the external boundary of the part by using Sobel Edge detection Algorithm.
2. Find the lines in the external boundary of the part using Hough Transform.
3. Find corner points in image using Shi and Tomasi's minimum eigenvalue method [13].
4. Cluster together corner points which are near to each other by taking median.
5. Label corners and connecting lines by designating leftmost line as L_1 and bottom left corner point as C_0. Therefore L_n is connected by C_{n-1} and C_n corners respectively.
6. If feature is stepped feature, measure the length of the line segment, to measure the length of the step.
7. If feature is taper feature, measure the length of the line segment, as well as angle with the Part Axis to measure the feature.

Once all the geometric features are extracted from all the 3 views of the object, these geometric features are interpreted as machining features, as described in the next section.

2.2.4 Feature Interpretation

In order to encode the part into an m x n matrix code, all the geometric features extracted in the previous section need to be interpreted as machining features, and a classification and coding system namely, codex that we have evolved is used to denote each of the features in the 4 x 3 matrix.

2.2.4.1 Part Classification

The codex is a simplified version of Opitz [14] Classification system, consisting of 5 digits describing the form of the part and remaining 4 digits describing the material and dimensions of the part. We would be describing the part with just its form and dimensions, plus application of machine vision is limited to identification of some simple features like steps, taper, holes, etc., therefore, the codex used only describes these features in the part. The codex is a key which is used to encode the part into a 4 x 3 matrix format with its basic structure shown in Table 1.

$$\begin{bmatrix} A & B & C & D \\ A_1 & B_1 & C_1 & D_1 \\ A_2 & B_2 & C_2 & D_2 \end{bmatrix}$$

Table 1 Key for 4X3 Part Coded Matrix

A	SHAPE	B	HOLES	C	EXTERNAL	D	PERIPHERY
1	Rotational part	0	No holes	0	Cylinder feature	0	None
3	Triangular part	1	Through holes	1	Stepped feature	1	Pitch circle
4	Rectangular part	2	Blind holes	2	Taper feature	2	External Thread
6	6 sided part	3	Through & Blind	3	Stepped & Taper	-	-
A_1	**ROTATIONAL DIMENSIONS**	B_1	**THROUGH HOLES**	C_1	**STEPPED**	D_1	**PITCH CIRCLE**
1	L/D ≤ 0.5	N	Number of holes	A.B	A = Number of steps (Front) B = Number of steps (Back)	N	Number of holes
2	0.5 ≤ L/D ≤ 3						
3	L/D ≥ 3						
A_2	**NON-ROTATIONAL DIMENSIONS***	B_2	**BLIND HOLES**	C_2	**TAPERED**	D_2	**EXTERNAL THREAD**
1	A/B ≤ 3 A/C ≥ 4	A.B	A = Number of holes (front) B = Number of holes (back)	A.B	A = Number of taper (Front) B = Number of taper (Back)	A.B	A = Number of threads (Front) B = Number of threads (Back)
2	A/B > 3						
3	A/B ≤ 3 A/C < 4						

* A,B – Top View, C – Side View

Examples of codes of a few parts are given in Table 2.

Table 2 Examples of Coded Parts

	$\begin{bmatrix} 1 & 0 & 3 & 0 \\ 3 & 0 & 1.2 & 0 \\ 0 & 0 & 1.0 & 0 \end{bmatrix}$
	$\begin{bmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 1.0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$

The first row of the matrix describes the family, to which the part belongs to. The subsequent rows provide further information which is utilized for part identification.

2.2.4.2 Part Identification

In order to identify a part under inspection as a known part, its matrix code is compared with standard matrix codes which have already been registered with the system. If a match is found, then the part is identified as that part, for example, a bushing has a code of say, $\begin{bmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 1.0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$, which is then compared with the code of the part under inspection, if there is a match between the codes, then the part is identified as a bushing. If a match is not found, then that part code is added to the database of known parts in the system.

2.2.4.3 Dimension Inspection

The above table describes the interpretation of the 4x3 part matrix for encoding a part into constituting features extracted from image analysis. In order to supplement the above matrix, a supplementary coded array is generated consisting of all the dimensions associated with the features described in the part matrix. It utilizes the information provided in primary matrix to store all relevant dimensions in a systematic format. The matrix is traversed in column-wise fashion and each non-zero element of the matrix has associated dimensions. Though each element in the matrix has single or multiple dimensions associated with it, which is stored correspondingly. For example, a rotational component has diameter and length as primary dimensions, whereas a non-rotational prismatic feature has length, width, and height as primary dimensions. This concept is further exemplified by Table 3. Here each cell describes the dimensions associated with corresponding feature in Table 3, and number of features multiplies the dimensions.

Table 3 Feature Dimensions and their Sequence

A – Shape dimensions	B – Holes Dimensions	C – Steps/Taper Dimensions	D – Pitch Circle, Threads
A_1 Diameter and Length of rotational feature	B_1 Diameter1, Diameter2, ... no of through holes	C_1 Diameter1, Length1, Diameter 2, Length 2, ...no. of steps	D_1 Number of Holes in Pitch Circle, Pitch Circle Diameter
A_2 Length, Width, Height of prismatic feature	B_2 Diameter1, Diameter2, ... no of blind holes	C_1 BigDiameter1, Angle1, SmallDiameter1, BigDiameter2, Angle2, SmallDiameter2,... no. of tapers	D_2 Pitch1, Length1, Pitch2, Length2, ... no. of threads

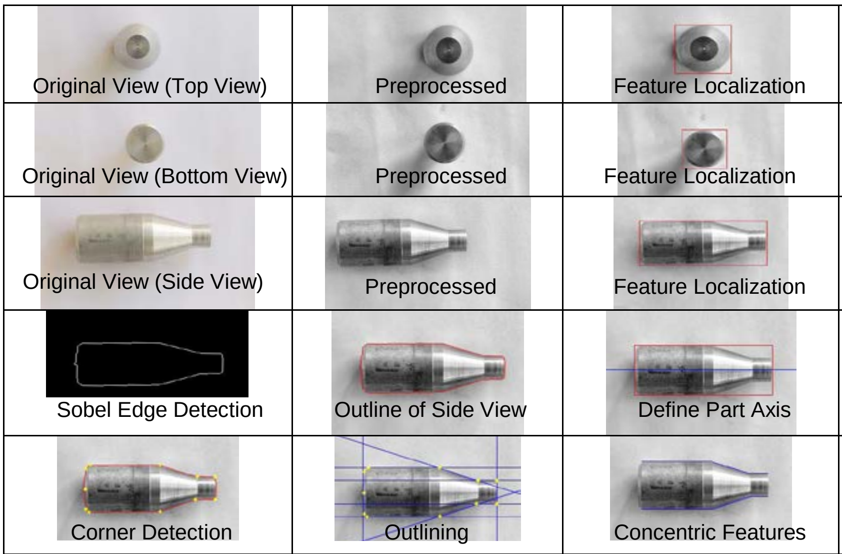
Therefore the rotational part shown in Table 2 will have a dimension array like,

$$\begin{bmatrix} D & L & D_1 & L_1 & D_2 & L_2 & D_3 & L_3 & BD_1 & A_1 & SD_1 \end{bmatrix}$$

where, D, L are part dimensions, D1…L3 are step dimensions, and BD1, A1, SD1 are taper dimensions. These dimensions are then checked with standard dimensions of the part and error in each dimension can be calculated. If the error is within the tolerance limit, then the part is passed, else the part is failed.

3. RESULTS AND DISCUSSIONS

The above methodology is implemented using MATLAB which provides an inbuilt image processing toolbox, with various functions that prove to be useful for programming this methodology. The program is run on a rotational part consisting of stepped features. The results and intermediate steps are given in the Fig. 1.



$$\begin{bmatrix} 1 & 0 & 3 & 0 \\ 2 & 0 & 1.0 & 0 \\ 0 & 0 & 1.0 & 0 \end{bmatrix}$$

Matrix Code

Dimension Array = [2.48 7.1 1.0 1.0 2.48 -18.5 1.0]
Standard Array = [2.5 7.0 1.0 1.1 2.5 -20 1.1]
Error Array = [0.008 0.014 0 0.9 0.008 0.075 0.9]

Fig. 1 Results for a Sample Part

4. CONCLUSIONS

The methodology described is an attempt for automating inspection in manufacturing by use of machine vision system. This is achieved by using image processing techniques to extract geometric information from images of the mechanical components, and then interpreting them as features to describe the mechanical component. This feature description is stored as a coded matrix which serves not only as an identifier but also as a group technology code to classify parts into families. This has added benefits in manufacturing and process planning as discussed above. The image processing methodology developed gives promising results provided the image of the part under inspection is focussed, well illuminated, and sharp. The descriptor matrix used is a simplified version of more elaborate Opitz coding system for part classification, and presently the methodology works on parts with simple features such as holes, steps, tapers, etc. For more complicated features such as grooves, chamfers, fillets, etc., the algorithm needs to be further extended. Furthermore, the methodology can be extended to inspect not just mechanical components, but also mechanical assemblies as well.

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