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COMPUTER VISION BASED INSPECTION OF MACHINED PARTS BY MATHEMATICAL SHAPE MODELING

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Abstract In this paper, machine vision algorithms have been developed for inspection of manufactured parts. A mathematical shape modeling procedure has also been presented. The whole technique has been composed of various modules, e.g., sharp break point detection, smooth break point detection , straight line segments and circular arc detection and recognition. From the two-dimensional profile of a manufactured part as represented in terms of ordered contour points, the break points have been first detected. Then, the boundary has to be segmented assuming that the boundary would consist only of straight lines and circular arcs. These straight segments and circular arcs have been found out and the relations among those have been analyzed. It has been observed that with this scheme, it has been possible to compress the data to a large extend and hence, to save the computer storage space. With the application of this methodology, input objects have been classified by matching with the stored information of the reference classes. However, this technique can easily be made programmable to include new reference images.

Keywords: Contour-tracing, Sharp-break points, Smooth-break points, Shape- modeling.

INTRODUCTION

With the advancement of manufacturing technology and precision product manufacturing, application of machine vision techniques to industrial inspection problems has received a great deal of attention. The objective of this paper has been to develop a machine vision system for shape recognition and analysis so as to improve the performance and efficiency of computer integrated manufacturing system. In this paper, only the planar profiles have been considered which have been obtained by the projection of three-dimensional manufactured parts onto the two-dimensional inspection plane and the boundary of which have been composed only of straight line segments and circular arcs. This assumption has been made depending on the fact that the straight line segments and circular arcs have been the most common and most frequently used entities in engineering design.

ELEMENTS OF COMPUTER VISION SYSTEM

The operational module of the vision system has been designed and developed so as to consist of (i)a sensing or imaging device which would produce the required analog signals, (ii)an A/D converter which would convert the analog signals as acquired by the sensing device to the digital form so as to make it perceptible by the central processor which would interpret and analyze the information and display the results . The elemental hardware setup of the developed computer vision system as used for recognition of the manufactured parts would comprise of the following features, e.g.;

(a) A high resolution CCD color camera with 756(H)X581(V) pixel imager;
(b) Two regulated 12V D.C., 1.2 A power supply;
(c) One super VGA high resolution multi sync color monitor;
(d) One Host computer with necessary peripherals;
(e) One MVP-AT processor card fitted with the host computer; and
(f) Back lighting illumination system.

The details of the developed vision-based inspection system for analyzing and recognition of the manufactured parts have been as shown in Fig 1.

CONTOUR TRACING ALGORITHM

A curve in a digital picture can be represented as a sequence of integer coordinate points $p_0, p_1, p_2, \ldots\ldots p_{n-1}$, where if p_k and p_{k+1} have been two successive digitized points, then p_{k+1} must be one of the total eight neighbors of p_k including all horizontal, vertical and diagonal neighbors [Rosenfeld and Kak, 1976, Gonzalez and Woods, 1993]. Based on this assumption, a contour tracing algorithm has been developed to represent the closed contour as a set of digitized points.

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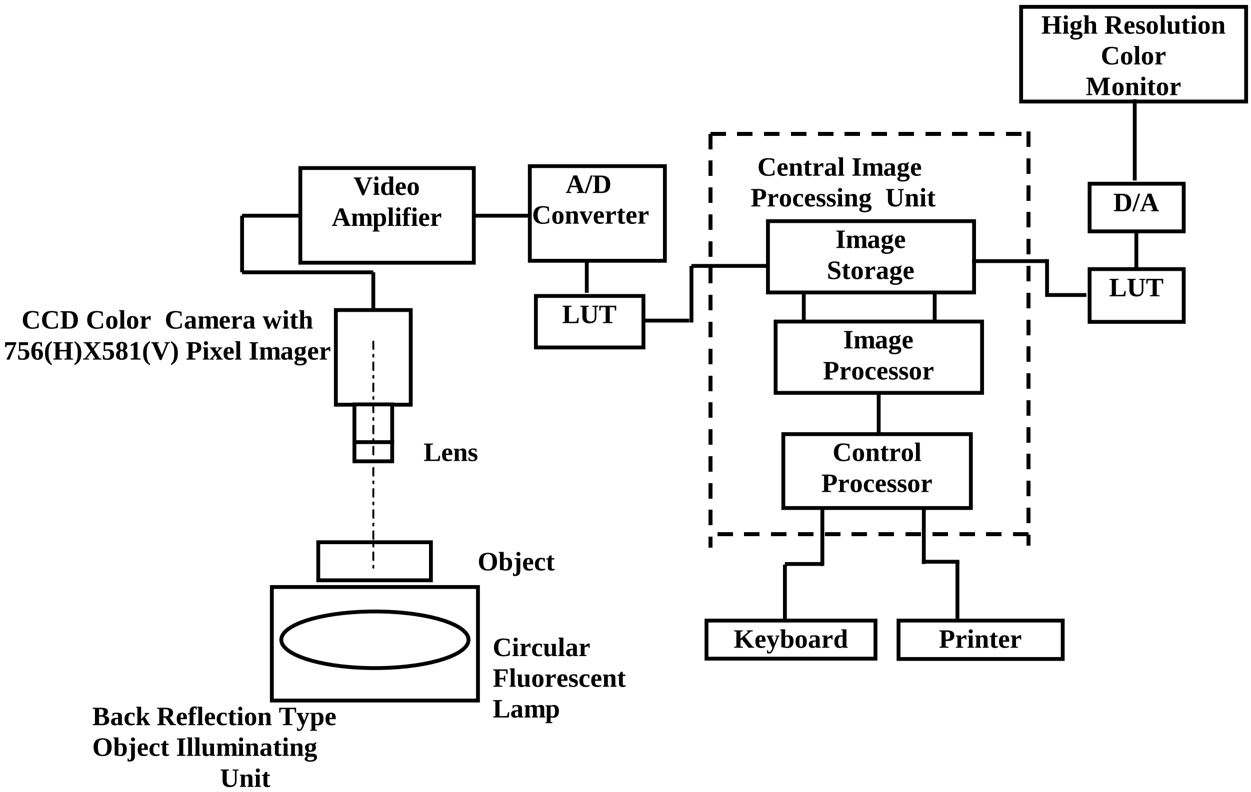

Fig.1 Elements of the Developed Computer Vision System

The grabbed image has been threshold by making the image pixels black against the white background. The image has been scanned row-wise from left to right. On scanning row-wise, when the first black pixel (let 'a' in **Fig 2**) has been detected, then its coordinates have been entered in the set of boundary points, pixel 1 in the eight neighbors of 'a' has been tested and checked whether it would satisfy all the conditions for being in the set of boundary points. The referred conditions are:

(i) It must be a black pixel ;
(ii) It must not already been entered in the set of boundary points ;
(iii) Referring to Fig. 3 either (1 and 3 must have opposite gray levels) or (2 and 4 must have opposite gray levels) or both the pairs may have opposite gray levels.

If all the conditions are not satisfied by 1 then pixel 2 in the eight neighbors of 'a' has been considered and checked whether it would satisfy all the conditions for being in the set of boundary points. If all the conditions are not satisfied by both 1 and 2, then pixel 3 in the eight neighbors of 'a' has been considered and checked whether it would satisfy all the conditions for being in the set of boundary points. On finding the second boundary point, it has been entered in the set of boundary points. For all the other boundary points, the pixels in the eight neighbors of the most recent boundary pixel have been considered one by one and checked which pixel would satisfy all the conditions for being in the set of boundary points. The process would stop if no more pixels can be found. In fact, at this point, all the boundary pixels have been entered in the set of boundary pixels and the boundary has already been closed. The implementation of this scheme has

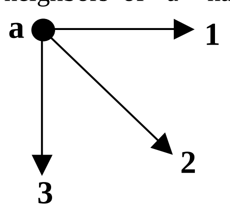

Fig. 2 'a' is the first pixel, The arrows show the pixels considered for the second digitized point.

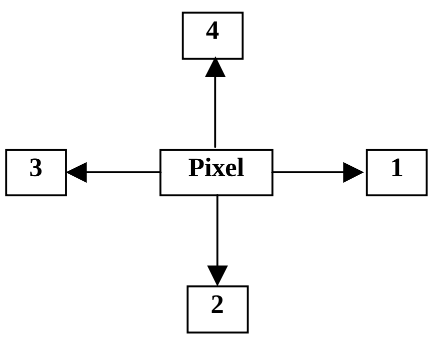

Fig.3 1,2,3 and 4 are the four neighbors of a pixel

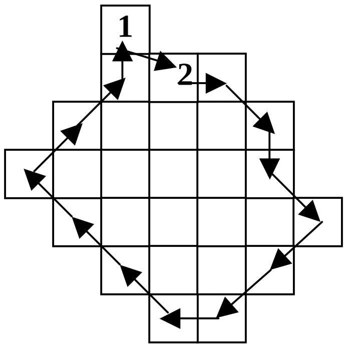

Fig. 4 Implementation of the Contour Tracing Algorithm

been represented in Fig. 4 where 1 and 2 would represent the first and second boundary pixels respectively and the arrows represent the sequence of the boundary pixels. The developed algorithm can be represented completely by the following steps:

Step I: Threshold the image by making the image of the object black(0) and the background white(1).

Step II: Scan row-wise until the first pixel (x,y) with gray-level (0) has been detected. Enter it into an array contour.

Step III: x=x+n; where, n=processing speed.

Step IV: If gray-level of (x,y)=0, then
{ if(x-n,y) and (x+n,y) has opposite gray-levels
or
if(x,y-n) and (x,y+n) has opposite gray-levels }
enter (x,y) in contour. If number of contour elements would not increase, go to step VIII.

Step V: If step IV would fail, y=y+n; go to step IV.

Step VI: If step V would fail, x=x-n; go to step IV.

Step VII: Consider a pixel (x,y) in $N_{8(p)}$ with gray-level 0 and if (x,y) does not belong to contour, go to step IV.

Step VIII: Stop.

THE PROPOSED INSPECTION SCHEME

The input to the developed system would be the set of ordered boundary data as extracted from the object being inspected by the contour tracing algorithm. The whole technique has been composed of three modules: corner detection, segmentation and recognition. The first module of the technique would detect the corners in the image profile by the principle of maximum curvature. Next, in the second module, the boundary has been segmented into the straight line segments and circular arcs. In the third module, the observed profile shapes along with their relations have been compared with those of the reference shapes and hence, the recognition has been performed. The results obtained from this technique have been observed to be very accurate and reliable, which would never allow the false acceptance or rejection of the manufactured parts and hence, the quality of manufacturing would be maintained up to the margin.

Detection Of Sharp Break Points

The first module of the proposed technique would deal with the detection of the sharp break points in the image profile of the manufactured part. From the data as obtained through B-Rep(Boundary Representation), the vertices of a two-dimensional face have been determined. For doing so, the curvature for all contour points have been determined. For the ith point, the curvature can be estimated by finding the angle between the (i-k)th, ith and (i+k)th points. A sharp break point can be identified if the curvature has been obtained above a given threshold and has been a local maximum within a range [i-k,i+k] (Liu and Srinath, 1990).

Detection Of Smooth Break Points

Next, in the second module, smooth break points have been detected to be the points which would not be the sharp break points and beyond which, the curvature along the profile would start changing.

Segmentation

This module would deal with the segmentation of digitized planar curves into the straight line segments and circular arcs. After the detection of break points in this module the approximate functions (straight lines and arcs) have been fitted to the data intervals that have been separated by the break points. The number of primitives (n) which can be arcs or straight line segments would be same as the number of break points. The boundary data which have been arranged in clockwise direction can be partitioned into n number of data subsets,

$$S=\{p_j=(x_j,y_j),\ j=1,2,\ldots\ldots,m\} \quad (1)$$

$$S_i=\{(x_{i,j},y_{i,j})\ ,\ j=1,2,\ldots..,m_i\},\quad i=1,2,\ldots\ldots..,n$$

Each subset of data has been approximated by a line ($\boldsymbol{L}_i$) or an arc ($\boldsymbol{C}_i$) [Chen and Ventura ,1995]; i.e.,

$$S_i = \begin{cases}\boldsymbol{L}_i\ , \text{ for } i \in I_l\ , \\ \boldsymbol{C}_i\ , \text{ for } i \in I_c\ . \end{cases} \quad (2)$$

where I_l and I_c have been the sets of straight line segments and circular arcs respectively.

Let, $I = I_l + I_c$, then , $n_l + n_c = n$,

where, n_l =number of straight line segments,
n_c=number of circular arcs.

Recognition

In this module, classification of the input object as represented by n_l line segments and n_c circular arcs have been carried out based on the stored images. Let, O would represent a set of reference objects as defined by, O={ O_n, n=1,2, ………,N } , where N would be the maximum number of primitives ,i.e., straight line segments or circular arcs that a reference image may possess.

Shape recognition has been performed in two steps ,i.e., shape modeling and matching. In the shape modeling step, the primitive features in the image of the object have been identified along with their sequence. In the shape matching step, an attempt has been made to correspond between the sensed image and reference images.

Shape modeling

The developed scheme can be represented by: (1) the set of primitives that a particular shape can be decomposed into and (2) a set of relations among the primitives. Therefore, a reference image RI can be defined by a 3-tuple,

$$RI=(G,P,R), \qquad (3)$$

where, G: Number of primitives extracted from an image;

P: Set of boundary primitives defining a Particular shape which would be Straight line segments and circular arcs, and,

R: The set of geometric relations among the elements in P, for example, the angle between the two consecutive primitives.

Hence, G would describe a shape only by the total number of primitives, the maximum number of which has been a value equal to N.

$$G=n, \quad n=1,2,…………,N. \qquad (4)$$

$$P= \{P_i = (l_i,c_i,t_i) \ , \ i=1,2,…………,n\}. \qquad (5)$$

where l_i would represent the length of primitive P_i , which would be the straight line distance between the starting and end point of the primitive; and c_i would represent the curvature of P_i which can be approximated by the reciprocal of the radius of the primitive.

If the curvature has been found to be zero, then the primitive would be a straight line, else it would be a circular arc. If the primitive has been a straight line, then the value assigned to represent its type would be, $t_i=\phi$. If the midpoint of the straight line joining the starting point and end point of the circular arc would be a white pixel, then it would be a depression curve. The value assigned to represent the type would be, $t_i=0$. If the midpoint of the straight line joining the starting point and end point of the circular arc would be a black pixel, then it would be a protrusion curve. The value assigned to represent the type would be, $t_i= 1$.

Finally, the geometric relationship in this model has been defined by,

$$R= \{ R_i, \quad i=1,2,…………,n\}. \qquad (6)$$

where R_i has been the angle between two consecutive primitives.

Shape matching

For shape matching, the object image 3-tuple (G_0,P_0,R_0) has to be compared with the reference image 3-tuple (G_{ri}, P_{ri}, R_{ri}), where, i= 0,1,2, ……..,m-1; and m would be the number of reference models. The developed algorithm for shape matching can be described as follows:

For i=0 to m-1, if, G_0 # G_{ri}, then the object image would not match with the set of reference images, then goto stop.

Keep track of all the i value (values) for which G_0 = G_{ri} . For this set of r_i, compare P_0 with P_{ri} considering the 3-tuple (l_{ir},c_{ir},t_{ir}) and within a considerable tolerance for l_{ir} and c_{ir} .

If for all the reference images no matching has been obtained, then the object image would not match with the set of stored reference images, then goto stop.

Modify the i value (values) for which P_0=P_{ri} considering the values of the 3-tuple (l_{ir},c_{ir},t_{ir}) .

For the modified i values, if {R_i}#{R_0 ± tolerance}, then the input object image would not match with the set of reference images; goto stop.

Find the i for which the set of relations of the reference image would match with the set of references of the object image both in magnitude and sequence. The object would match with the i^{th} reference model.

Stop.

ANALYSIS

Since the recognition module would classify the object into one of the reference types, the subsequent analysis would be a model-based approach, the purpose of which has been to match the input shape as represented by the n data subsets, S_i , i=1,2, ………,n with a predefined model. The image profiles have been composed of straight line segments and circular arcs and all the elements and spatial relationships between

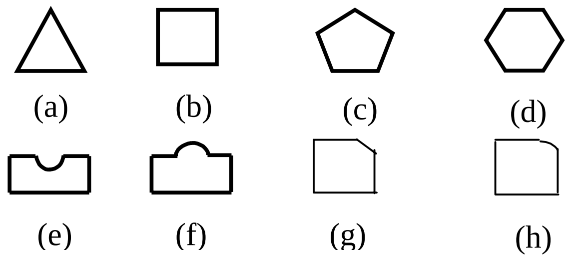

Fig. 5 Machined Parts to be treated as Reference Objects

those have been defined by the dimensional and angular specifications. The dimensions would include the lengths of the straight line segments and the radii of the circular arcs and the angles would include the relative angles between two adjacent elements.

The complexity of the proposed algorithm has been O(m), regardless of the number of entities(n). The developed system can be used to handle the analysis of the planar profiles with any combinations of lines and curves, and the computational time has been proportional to the number of sampled pixels.

Image acquisition and storage using the reference shapes as shown in Fig. 5 have been conducted through the developed set up. The experiments have been carried out on a Host computer using Microsoft C for the storage of the reference images.

The numerical results have been shown in Table 1 , where the first two columns would describe the parameters of the input data, such as the corresponding figure number and the number of entities(n). Column 3 would describe the specifications of the boundary primitives in terms of l_i, c_i and t_i and column 4 would describe the relations among the primitives. These results have been stored for classification of the unknown objects.

EXPERIMENTAL RESULTS AND STUDIES

With the help of Table 1 in which the details of the reference shapes have been stored, the shapes of the objects as shown in Fig . 6 have to be classified. The results have been displayed in Table 2.

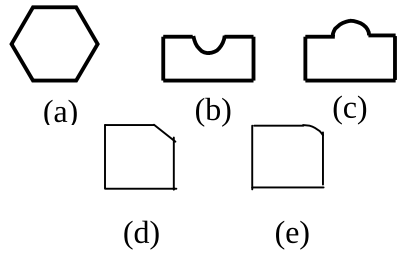

Fig.6 Objects to be matched with the References

CONCLUSION

In this paper, a machine vision inspection system for manufactured parts have been presented. For the grabbed image, the ordered contour points have been found out. In the next phases, the detection of corners, segmentation of the profile, recognition and analysis have been performed. In this paper, the three-dimensional machined parts have been projected in the two-dimensional inspection plane and the recognition modules have been applied to the two-dimensional planar profiles. The planar profiles have been considered to consist of only straight line segments and circular arcs, as roundness and straightness have been found to be the most frequently used geometric entities in engineering design and manufacturing. The shape modeling scheme as described would compress the data to a large extend and hence, would save computer storage space and the shapes can be expressed in a compact and meaningful form. Another advantage of the methodology would be that it could easily be programmable to include new reference images .

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Table 1:Various Parameters of the Reference Objects

Fig	G	$P=\{(l_1,c_1,t_1)\ldots\ldots(l_n,c_n,t_n)\}$	$R_1\ldots\ldots R_i$ (angle in degrees)
(a)	3	{(78.60,0, ϕ),(62.80, 0, ϕ),(73.99, 0, ϕ) }	60,60,60
(b)	4	{(65.00, 0, ϕ),(69.00, 0, ϕ),(66.06, 0, ϕ), (69.55, 0, ϕ) }	90,90,90
(c)	5	{(50.50, 0, ϕ),(52.60, 0, ϕ),(56.00, 0, ϕ), (54.00, 0, ϕ),(52.00, 0, ϕ) }	72,72,72,72,72
(d)	6	{(41.50, 0, ϕ),(46.00, 0, ϕ),(40.00, 0, ϕ), (40.00, 0, ϕ),(42.00, 0, ϕ),(44.00, 0, ϕ) }	60,60,60,60,60
(e)	6	{(50.00, 0, ϕ),(51.00,.039,0),(50.00, 0, ϕ), (65.26, 0, ϕ),(151.00, 0, ϕ),(65.25) }	90,90,90,90,90,90
(f)	6	{(50.00, 0, ϕ),(50.50,.0396,0),(50.00, 0,ϕ) ,(65.26, 0, ϕ),(151.00, 0, ϕ),(65.25) }	90,90,90,90,90,90
(g)	5	{(30.50,0, ϕ),(22.53, 0, ϕ),(27.75,0, ϕ), (45.00, 0, ϕ),(45.00, 0, ϕ) }	50,40,90,90,90
(h)	5	{(30.50,0, ϕ),(22.53, 0, ϕ),(27.75,0, ϕ), (45.00, 0, ϕ),(45.00, 0, ϕ) }	0,0,90,90,90

Table 2: Various Parameters of the Test Objects

Fig	G	$(l_1,c_1,t_1)\ldots\ldots(l_n,c_n,t_n)$	$R_1\ldots\ldots R_i$ (angle in degrees)	Inference
(a)	6	{(41.38, 0, ϕ),(46.08, 0, ϕ),(39.95, 0, ϕ), (40.04, 0, ϕ),(42.07, 0, ϕ),(44.07, 0, ϕ) }	60,60,60,60,60	Matches with the reference part representing the hexagon
(b)	6	{(50.00, 0, ϕ),(51.00,.039,0),(50.00, 0, ϕ), (65.26, 0, ϕ),(151.00, 0, ϕ) ,(65.25) }	90,90,90,90,90,90	Matches with the reference part with a depression arc
(c)	6	{(50.00, 0, ϕ),(50.51,.0396,0),(50.00, 0,ϕ), (65.26, 0, ϕ),(151.00, 0, ϕ) ,(65.25) }	90,90,90,90,90,90	Matches with the reference part with a protrusion arc
(d)	5	{(30.50,0, ϕ),(22.53, 0, ϕ),(27.75,0, ϕ), (45.00, 0, ϕ),(45.00, 0, ϕ) }	50,40,90,90,90	Matches with reference part with a chamfer
(e)	5	{(30.50,0, ϕ),(22.53, 0, ϕ),(27.75,0, ϕ), (45.00, 0, ϕ),(45.00, 0, ϕ) }	0,0,90,90,90	Matches with the reference part with a fillet