

Integration of Vision and Laser Displacement Sensor for Efficient and Precise Digitizing

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Abstract—This paper presents a new digitizing technique which integrates computer vision methods, such as the photometric stereo approach, with the laser displacement sensors (LDS). The curvature at each point of the surface can be measured cost-effectively by the photometric stereo approach. Once the information of curvature of the surface is provided, the measuring speed of LDS can be improved by digitizing at the selected points of the surface and meanwhile the accuracy of digitization is still maintained. By means of the integration, the merits of both approaches can be achieved simultaneously and the efficiency of the digitization can be improved. Experimental results are provided to verify the proposed method.

I. INTRODUCTION

IN the manufacturing industry, "reverse engineering" becomes an indispensable ingredient of the production process. The reverse engineering, together with the rapid prototyping, shortens the design cycle and improves the design quality [1]. Many rapid prototyping techniques have been developed and become mature recently [2], [3]. The main advantage of the rapid prototyping is the speed. Once the CAD model of an object is given, the replica can be reproduced quickly. However, in many situations of the manufacturing industry, the prototypes are still made of clay or wood solely by human hands and thus the corresponding CAD models are not available. Reverse engineering, therefore, is designed to acquire the three-dimensional measurement of an object.

The reverse process for obtaining the surface profiles of the prototypes by using computerized machines has several advantages: First, the reproduction of the prototypes becomes easier and more efficient. The CAM is designed for this purpose. Secondly, the defects of the prototypes can be examined and thus the CAD modification can be made more successfully and effectively. Moreover, the computerized data of the prototype surfaces can be tested through computer simulations in which, for example, the parameters of strain, torque, and elasticity tolerance can be calculated and further improved. Therefore, reverse engineering has been already applied practically to mobile, aviation, manufacturing, and military industry.

In order to obtain mathematical descriptions of the prototypes, these models must be digitized either manually or by computerized devices. Since the technique of digitizing influences the quality of the parts to be manufactured in the

production process, how to achieve efficiency and precision in digitizing becomes an important issue in the manufacturing industry [4]–[8].

Many digitizing devices have been developed for different demands and working environment in the manufacturing industry. Puntambekar, *et al.*, presented a good review of the techniques available for the reverse engineering with particular emphasis on the three-dimensional model measurement [9]. These digitizing devices can be roughly divided into two categories.

- 1) Contacting devices: The most representative example is the coordinate measuring machine (CMM). A touch probe is usually mounted on the CMM to contact the surface in order to obtain the depth values [10]. However, in many situations of the manufacturing environment, contacts on target objects might not be permitted since it can cause damages to fragile objects or such a measurement may lose its accuracy if the objects are made of elastic or soft material. Other examples of contacting devices are to use electromagnetic or sonic sensors [11], [12]. Due to the natural limitation of the devices, these two sensors are not as widely accepted as CMM.
- 2) Noncontacting devices: The major noncontacting digitization is to use the optical sensors. Some of the prevalent techniques are listed as follows.
 - a) The photometric stereo approach uses the fact that under the same viewing direction, different illuminating conditions of an opaque object result in different shading effects [13]. The gradients of each element on the surface can therefore be obtained. Integrating all the gradients gives one the depth information of the surface.
 - b) The striped lighting (structured lighting) approach scans the surface with a sheet of light [14]. This sheet of light sweeping across the scene produces a single light stripe at each position. By measuring the degree of distortion of the light stripes, the shape of the object can be determined. Since many light stripes need to be analyzed, the process of computation is complicated and very difficult to be done in real time.
 - c) The dual camera approach utilizes the same principle of the binocular stereo as in the way the human eyes do [15]. The key feature is that the points of the stereo images taken from the dual cameras must be matched. Then the disparity between two corresponding points can be utilized to extract the

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three dimensional depths. It is time-consuming to match all the points or even the features in the two images and a well calibration of cameras is needed in advance.

- d) A dynamic focusing technique was proposed by Brown [16]. A laser diode is used for the purposed of focusing. The measurement precision is claimed to be reached up to $50 \mu\text{m}$.
- e) The laser displacement sensor (LDS) can gain high precision and resolution. A focused laser beam reflected from the spot of the surface is received by an array of CCD sensors. The position of the activated pixel of the CCD array gives one the displacement depth between the target spot and the origin of the laser beam. This point-by-point measurement of LDS is of high accuracy but unfortunately, the measuring process using LDS is slow when a large number of points on the surface need to be digitized. Also the precision of LDS is affected by the incident angle of the laser beam. Only when the laser beam is projected perpendicularly to the surface and the measured depth is within the stand-off distance, the LDS achieves its highest precision [17], [18]. Since the surface to be measured is unknown, keeping the laser beam perpendicular and adequately distant to the surface is very difficult if not impossible. In addition, the precision of LDS sometimes suffers from the optical characteristics of the target surface.

In this paper, in order to improve the efficiency and precision of surface digitizing, we propose to integrate the photometric stereo approach with the LDS to digitize unknown surfaces. The proposed approach utilizes the high speed of the photometric stereo approach and the precision of the LDS. The normal vector of each element on the surface is obtained using the photometric stereo approach. Realizing the fact that it is not necessary to digitize every point of the surface if some local areas of the surface are smooth enough, the points to be digitized by LDS are chosen according to the curvature distribution of the surface. The advantages of this integration approach are twofolds. First, the number of the digitizing points on the surface are reduced since digitizing can be sparse for those areas which are relatively smooth. Secondly, the orientation of the laser beam can be adjusted according to the normal vectors obtained from the photometric stereo approach. As a result, the LDS achieves its highest precision in digitizing and in the meanwhile the entire digitizing process becomes very efficient.

The structure of this paper is as follows. In the next section, the use of LDS in the digitizing process is introduced. In the third section, the proposed integration approach is presented. Experimental results using the integration approach are provided in the fourth section. The paper is concluded in the fifth section.

II. DIGITIZING AN UNKNOWN SURFACE USING LDS

The LDS can digitize an unknown surface without making contact with the surface. The current technology applies the

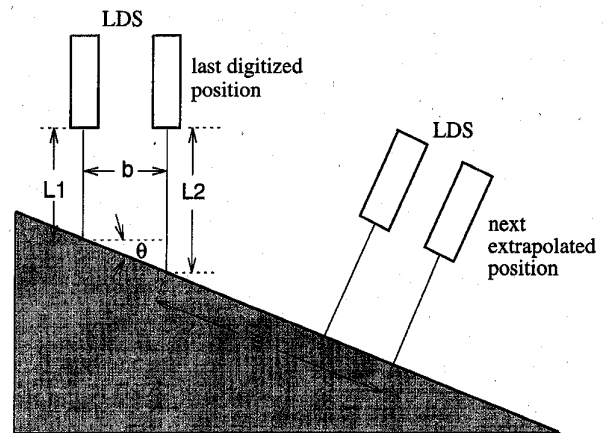


Fig. 1. Two-LDS approach.

triangulation method to the most commercially available LDS. Due to the optical characteristic of laser, a well-focused beam can be emitted from the LDS. After the laser beam spotting on the surface, the radiation of the diffuse light can be detected by an optical sensor such as CCD. The reflected spot on the CCD varies with the distance and incident angle between the LDS and the target surface. The displacement of the surface can thus be calculated from the position of the spot on the CCD sensor. The LDS can obtain a high resolution of measurement in the order of 10^{-6} m if the sensor is used in a proper manner. However, if the incident angle of the laser beam is not perpendicular to the surface, the light spot generated by the laser beam on the surface will have a larger area. This will reduce the resolution and precision of the CCD sensor. For example, the LDS manufactured by Keyence Corp. has an error as large as 1.25% of the measured distance if the laser beam is tilted by 30° from the normal vector of the measured point [17]. Therefore, the laser beam should be kept as perpendicular to the measured surface as possible during the digitizing process.

There are two categories of research devoted to improving the accuracy and reducing the orientation sensitivity of LDS. The first is to develop new internal structures of LDS. The effort of Saito and Miyoshi [4] is proven to be effective. The other strategy is to improve the digitizing scheme and tries to maintain the orientation as perpendicular to the surface as possible. Smith and Zheng [18] used multiple LDS's to extrapolate the surface normal vector of the next digitizing point [18]. In Fig. 1, two LDS's are placed with distance b apart and the digitizing depths are L_1 and L_2 , respectively. The angle of the tilt surface can then be expressed as

$$\theta = \tan^{-1}\left(\frac{L_2 - L_1}{b}\right) \quad (1)$$

where θ is the amount of angle that the laser beam has to be adjusted at the next digitizing point in order to keep the LDS perpendicular to the surface. If only one LDS is used, a prior estimation of the surface gradient at the digitizing points must be given. Otherwise, it will not be able to make the LDS perpendicular to the surface.

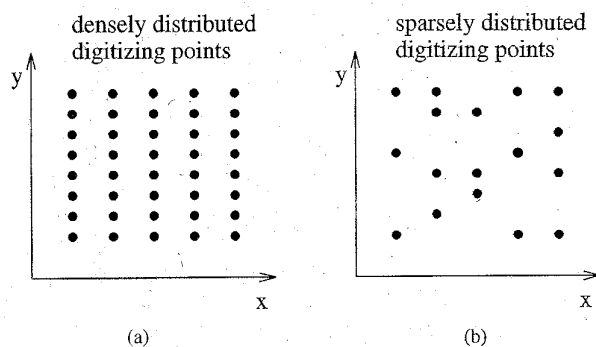


Fig. 2. Densely and sparsely distributed digitizing points.

Another reason for estimating the surface gradient is to reduce the number of digitizing points. Assume that the object surface to be digitized can be described by the following equation:

$$z = f(x, y). \quad (2)$$

When the LDS digitizes the surface, the digitizing (sampling) distance must be selected based on the highest curvature and must be evenly distributed on the x - y plane. These digitizing points form a dense grid on the x - y plane as shown in Fig. 2(a). If the curvature distribution of the surface can be estimated by the photometric stereo approach or any other methods, one can reduce the number of digitizing points. That is, make dense digitizing on high-curvature areas and sparse digitizing on low-curvature areas (see Fig. 2(b)). As a result, the time for digitizing the surface can be greatly reduced.

From the discussion of this section, one can see that the LDS can provide an efficient and precise measurement only when some preliminary information is provided. The photometric stereo approach can provide this preliminary information with a fast computation.

III. INTEGRATION OF PHOTOMETRIC STEREO AND LDS

A. Obtaining Gradients of the Surface Using Photometric Stereo

The photometric stereo approach captures three images of an opaque object under different illumination conditions with a fixed viewing direction. The brightness B in the images is a function of the gradients $p = dz/dx$ and $q = dz/dy$ if the radiant flux P and the reflectivity constant ρ are known. [15], [19]. The brightness can be expressed as

$$B(p, q) = \rho P \frac{1 + pp_s + qq_s}{\sqrt{1 + p^2 + q^2} \sqrt{1 + p_s^2 + q_s^2}} \quad (3)$$

where p_s and q_s are the gradients of the surface which is perpendicular to the light rays. In (3), p , q , and ρ are unknowns which varies with respect to the illuminated spots on the object. Therefore, at least three different images must be taken to constrain a unique solution. By solving the nonlinear equations of three images for each element on the surface, surface gradients p and q can be obtained for each digitizing

point. Since the photometric stereo approach is well known, the details of the approach will not be discussed here.

In addition to the photometric stereo approach, many other computer vision based methods can also be utilized to extract the 3-D information of an object. The usage of these methods is subject to the optical characteristics of the objects and/or the environment under which the measurement is undergone. For example, the photometric stereo approach can only be applied to the objects with the diffused property, i.e., the reflected light intensity is uniformly distributed in all directions. But for specular objects, the photometric stereo approach may not be an adequate choice. In this case, some modified photometric stereo methods [19], [20] can be employed to solve this problem. All of these computer vision methods have a common property: They can compute the result faster but less accurate than LDS. The errors resulted from the image noise, improper illumination and many other interferences often constitute in the deviation of measurement. However, this weakness can be compensated by a precise LDS digitizing which can greatly improve the accuracy. Also the rough curvature distribution obtained from photometric stereo methods can be used as a preprocessing step and thereafter can accelerate the digitization process of LDS. The details are explained as in the following sections.

B. Calculating the Curvatures from Three Normal Vectors

Once the gradients p and q of the digitizing points on the surface are obtained from the photometric stereo approach, the unit normal vector can be calculated as follows. Assume the equation of the plane passing through a point P is $ax + by + z = c$ and the gradients are p and q . Since $dz/dx = -a$, $dz/dy = -b$, and the normal of the plane is $(a, b, 1)$, the normal can be expressed in terms of gradient as $(-p, -q, 1)$. The unit normal at P can be obtained by normalizing $(-p, -q, 1)$, i.e., the unit normal vector is equal to $(-p, -q, 1)/\sqrt{p^2 + q^2 + 1}$.

To determine the digitizing distance, the curvature information at every digitizing point must be obtained. We use the unit normal vector of a digitizing point plus the unit normal vectors of its two neighboring digitizing points to find the curvature of the first digitizing point (how to select the two neighboring points will be discussed later). Fig. 3 illustrates the approach. Let S_1 , S_2 , and S_3 be three consecutive points on the surface. Their corresponding unit normal vectors, which are obtained from the photometric stereo approach, are \mathbf{n}_1 , \mathbf{n}_2 , and \mathbf{n}_3 . Let points $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, and $P_3(x_3, y_3, z_3)$ represent the end points of the unit normal vectors of \mathbf{n}_1 , \mathbf{n}_2 , and \mathbf{n}_3 . One has

$$\begin{aligned} x_1 &= S_{1x} + n_{1x}, & y_1 &= S_{1y} + n_{1y}, & z_1 &= S_{1z} + n_{1z} \\ x_2 &= S_{2x} + n_{2x}, & y_2 &= S_{2y} + n_{2y}, & z_2 &= S_{2z} + n_{2z} \\ x_3 &= S_{3x} + n_{3x}, & y_3 &= S_{3y} + n_{3y}, & z_3 &= S_{3z} + n_{3z} \end{aligned}$$

where S_{ij} and n_{ij} , $i = 1, 2, 3$ and $j = x, y, z$, represent the x , y , and z components of point S_i and vector \mathbf{n}_i respectively.

According to the definition of the radius of curvature, the circle passing through the points P_1 , P_2 , and P_3 can give us a curvature information which shows the depth change of the

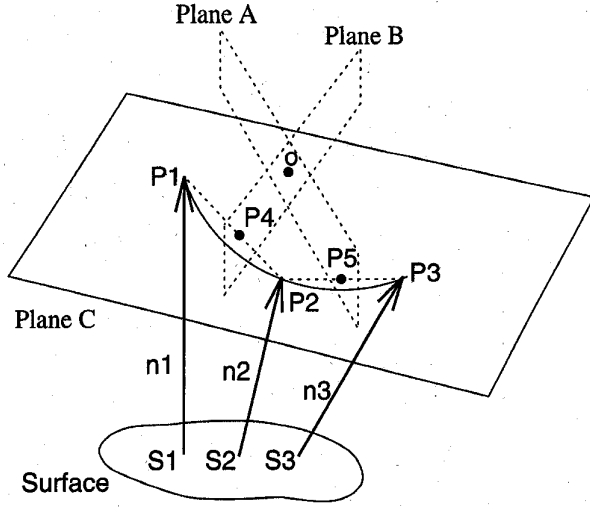


Fig. 3. The curvature calculation of three unit normal vectors.

points S_1 , S_2 , and S_3 on the surface. For example, if these three unit normal vectors are oriented in the same direction, the curve passing through P_1 , P_2 , and P_3 will be a straight line. Therefore, the curvature of this line is zero. On the other hand, if these unit normal vectors are different from each other, a circle which connects P_1 through P_3 can be calculated and the radius of this circle (radius of curvature) can be used as a measure of the curvature information.

Unfortunately, the depth information of the digitizing points is unknown; therefore, S_{1z} , S_{2z} and S_{3z} in the above three equations are unknown (note that S_{1x} , S_{1y} , S_{2x} , S_{2y} , S_{3x} , and S_{3y} are independent variables in (2)). We further assume that $S_{1z} = S_{2z} = S_{3z} = \text{constant}$. This assumption is reasonable when the digitizing points are very close and the depth change between two neighboring points is very small. With this assumption, the exact values of S_{1z} , S_{2z} , and S_{3z} are not needed when one estimates the curvature of a digitizing point.

Based on the above discussion, the calculation of the radius of curvature is illustrated as follows. Points P_1 , P_2 , and P_3 form a plane C . Points P_4 and P_5 are the midpoints of line segments $\overline{P_1P_2}$ and $\overline{P_2P_3}$ (see Fig. 3). Thus, one has

$$\begin{aligned} P_1 &= (x_1, y_1, z_1) \\ P_2 &= (x_2, y_2, z_2) \\ P_3 &= (x_3, y_3, z_3) \\ P_4 &= \left(\frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2}, \frac{z_1 + z_2}{2} \right) \end{aligned}$$

and

$$P_5 = \left(\frac{x_2 + x_3}{2}, \frac{y_2 + y_3}{2}, \frac{z_2 + z_3}{2} \right).$$

The planes A and B are bisecting and orthogonal to the line segments $\overline{P_2P_3}$ and $\overline{P_1P_2}$. The normal vectors of these two planes are

$$A: \left(\frac{x_2 - x_3}{2}, \frac{y_2 - y_3}{2}, \frac{z_2 - z_3}{2} \right)$$

$$B: \left(\frac{x_2 - x_1}{2}, \frac{y_2 - y_1}{2}, \frac{z_2 - z_1}{2} \right).$$

Thus the equations of A and B are

$$\begin{aligned} (x_2 - x_3)x + (y_2 - y_3)y + (z_2 - z_3)z \\ = [(x_2^2 - x_3^2) + (y_2^2 - y_3^2) + (z_2^2 - z_3^2)]/2 \end{aligned} \quad (4)$$

and

$$\begin{aligned} (x_2 - x_1)x + (y_2 - y_1)y + (z_2 - z_1)z \\ = [(x_2^2 - x_1^2) + (y_2^2 - y_1^2) + (z_2^2 - z_1^2)]/2. \end{aligned} \quad (5)$$

The equation of the plane C which P_1 , P_2 and P_3 form is as follows:

$$\begin{aligned} \begin{vmatrix} y_2 - y_1 & z_2 - z_1 \\ y_3 - y_1 & z_3 - z_1 \end{vmatrix} (x - x_1) + \begin{vmatrix} z_2 - z_1 & x_2 - x_1 \\ z_3 - z_1 & x_3 - x_1 \end{vmatrix} (y - y_1) \\ + \begin{vmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{vmatrix} (z - z_1) = 0. \end{aligned} \quad (6)$$

Assume that $S_{1z} = 0$, one may solve the equation set (4), (5), and (6) and the intersection point O can be obtained. The radius of curvature is the distance from point O to any one of the three end points P_1 , P_2 , and P_3 which all fall on the same circle.

C. Selecting Digitizing Points Using a 3×3 Mask

The steps described in the previous subsection determine the curvature at every point of the digitizing grid (Fig. 2(a)). In the following, we will select the points which must be digitized based on the curvature distribution. We apply a mask to every point of the grid. The mask is a subgrid of the whole surface with a size of 3×3 .

If a 3×3 mask is applied to a digitized point of a surface, the center point of the mask M_5 is the digitizing point at which we want to determine the curvatures of the surface (see Fig. 4). Then, it is clear that all the other elements of the mask, M_1 through M_9 , cover the neighboring digitizing points around M_5 (Fig. 4). For the 3×3 mask, there are four directions to calculate the curvatures. They are: $M_1 - M_5 - M_9$, $M_2 - M_5 - M_8$, $M_3 - M_5 - M_7$, and $M_4 - M_5 - M_6$, which are denoted by r_1 to r_4 , as shown in Fig. 4.

Based on the curvature information of the 3×3 block, the corresponding digitizing distance can be determined in each direction of M_5 . The rules of determination are as follows.

- 1) First, the x - y plane of the entire surface is divided into small blocks of 3 by 3 digitizing points.
- 2) For each 3×3 block, at center point M_5 , calculate the maximum curvature (minimum radius of curvature) in the four directions r_1 through r_4 using the methods developed in Subsection B.
- 3) Assume that the minimum radius of curvature of the entire surface is r_{\min} corresponding to the maximum curvature $1/r_{\min}$. By dividing $1/r_{\min}$ into m intervals, one can obtain m values which will be used as threshold values for determining the digitizing points, where m is a constant that needs to be selected. In general, a large maximum curvature needs a large m .

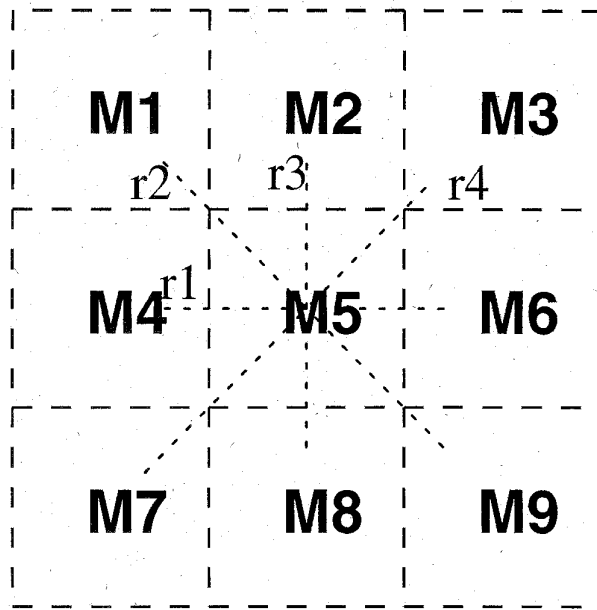


Fig. 4. Four choices of curvatures if a 3×3 mask is used.

- 4) For the direction with the radius of curvature being r_{\min} , all the three points along this direction in the 3×3 mask must be selected as the digitizing points because these points constitute the most curved profile.
- 5) For other curvature radii, one can determine the curvature intervals where they are lying based on the threshold values. For example, if in r_1 , the radius r_i falls in the region $[(m-j)/m \cdot 1/r_{\min}, (m-j+1)/m \cdot 1/r_{\min}]$, where $j = 0, 1, \dots, m-1$, the mask is expanded to $(2j+1) \times (2j+1)$ which is still centered by the same point M_5 . The digitizing points are the center point and the two farthest end points along the direction of r_1 . The points between these three points can be eliminated.
- 6) If the curvature radius r_i is in the smallest interval $[0, 1/mr_{\min}]$, the curvature is too small and no point on the 3×3 mask needs to be selected.

The above rules are applied to every point of the x - y plane of the surface. If a point of the evenly distributed grid as shown in Fig. 2 is never selected by any block, the point is removed from the grid. It is clear that by using the approach just described, the number of digitizing points can be reduced. This will make the digitizing process more efficient. Furthermore, because the gradients of the digitizing points are estimated by the photometric stereo approach, the LDS can be posed normal (or close to being normal) to the surface for those selected digitizing points. As a result, a more precise result can be obtained by the LDS.

To illustrate the use of the above the rules, an example is given below. In Fig. 5, Point 1 through Point 9 form a 3×3 mask and the curvatures in the four directions of r_1 to r_4 are denoted as r_1, r_2, r_3 , and r_4 respectively.

Assuming that m is selected to be 4, one can use the above rule in the following way.

- 1) If r_1 is the smallest radius of curvature of the surface, one can divide $1/r_1$ into 4 threshold values as shown

18			19			20
	10		11		12	
		1_{r_2}	2_{r_3}	3_{r_4}		
21	13	4_{r_1}	5_{r_1}	6	14	22
		7	8	9		
	15		16		17	
23			24			25

Fig. 5. Example for selecting digitizing points.

in Fig. 6 and can determine the region in which each radius is located.

- 2) Radius r_1 is in the Region I and therefore, Points 4, 5, and 6 must be selected as digitizing points.
- 3) Since r_3 exists in the Region II, the mask is therefore expanded to 5×5 and Points 11, 5, and 16 must be selected.
- 4) r_2 is located in the Region III. The mask is further expanded to 7×7 and Points 18, 5, and 25 are selected.
- 5) Finally, r_4 is in the Region IV with the smallest curvature. Since curvature is too small compared to others, none of the points in the direction of r_4 is selected.

The above rules can be applied to all the blocks of the surface.

IV. EXPERIMENTS

A. Equipment Setup

A Pulnix CCD camera and a point light source are mounted on two PUMA-500 robot manipulators, respectively. With the precise control of the robot, the position of the light source and the camera can be easily controlled. As a result, the information required by the photometric stereo approach can be easily obtained. The images captured from the camera are gathered in the Micro-VAX II minicomputer and are sent to the Sun Sparc Workstation for further processing. After the gradients at all elements of the grid are estimated and the digitizing points are selected, the camera is replaced by a Keyence LB-72/LB-12 LDS, and the surface is digitized at the selected digitizing points.

The setup of the experiment is shown in Fig. 7.

B. Result of the Experiment

A draw die model was digitized in the experiment. Since the model was obtained from General Motor Company, the

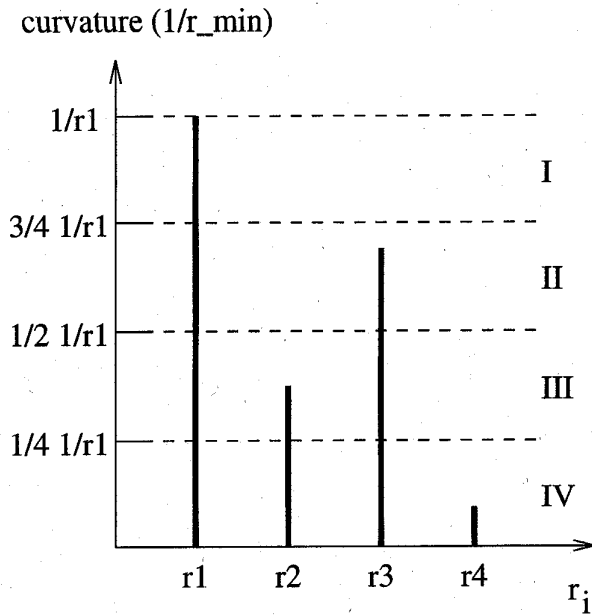


Fig. 6. Determine the digitizing distance by comparing the radius of curvature with the thresholds.

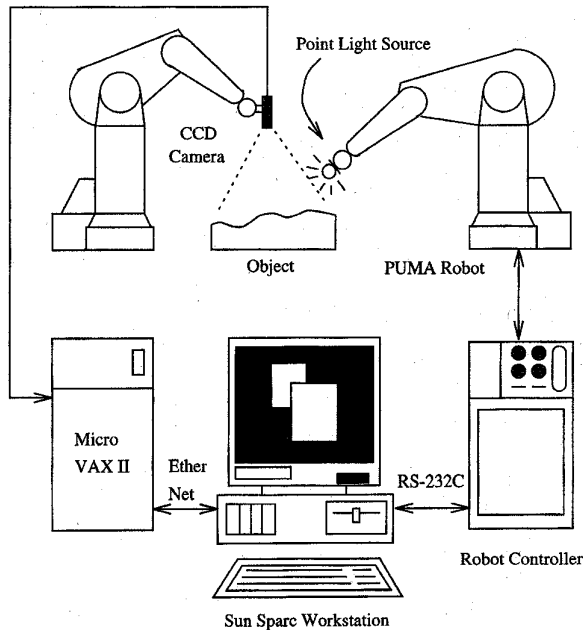


Fig. 7. Experiment setup.

term "GM draw die model" will be used in the remaining of this section. The GM draw die model has a smooth sculptured surface. To digitize the surface, we first determine the density of the original grid as shown in Fig. 2(a).

As mentioned in the context, the distance between two digitizing points on the original grid has to be based on the maximum curvature of the surface. We have used the following principle to determine the distance. Assuming that the radius of the maximum curvature is r , the sampling distance s should

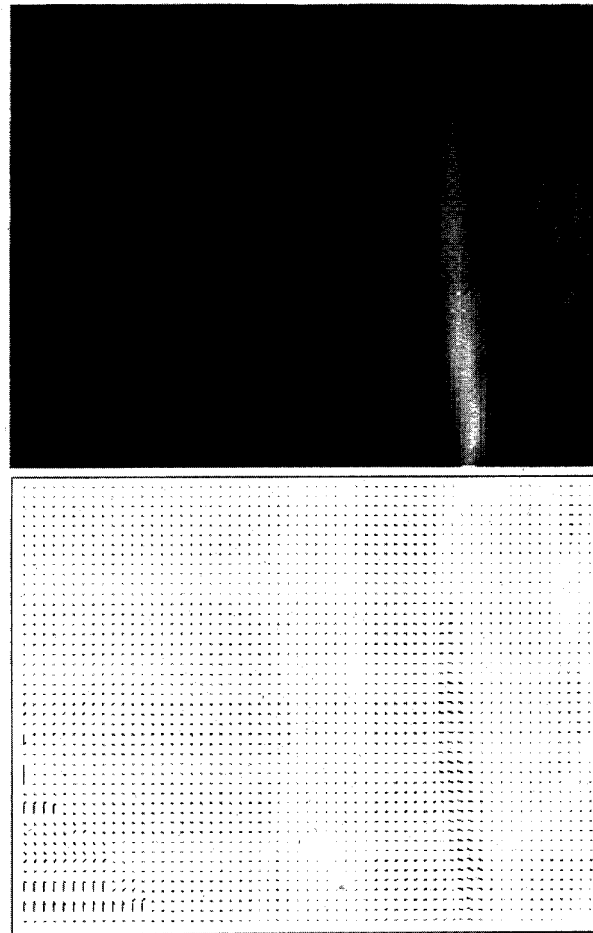


Fig. 8. The image and needle diagram of the GM draw die model.

satisfy the following inequality

$$s < r. \tag{7}$$

From the inspection of the draw die model, we estimated that the radius of the highest curvature of the surface was about 4 mm. To make it safe, we selected the sampling distance to be 3 mm. Since the GM draw die model covered an area of 240 mm \times 390 mm on the x - y plane, the evenly distributed grid has totally 10 400 digitizing points.

In the experiment, we first applied the photometric stereo approach to the model and obtained the normal vectors at digitizing points of the surface. The image captured from the CCD camera and the normal vectors (represented by needles) calculated from photometric stereo approach are shown in Fig. 8.

Then we used a 3×3 mask as described in the previous section to determine the curvatures in the four directions as shown in Fig. 4. The measured curvature was compared with the threshold values as shown in Fig. 6. The threshold values of the curvature for the GM draw die model were 1/3 mm, 1/4 mm, 1/6 mm, and 1/12 mm, respectively. Based on this consideration, the points which were finally selected to be digitized are shown in Fig. 9.

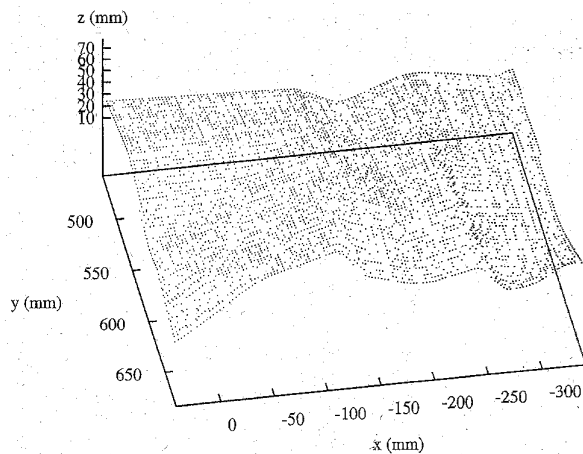


Fig. 9. The dots in the figure represent the digitizing points selected from a 3×3 mask.

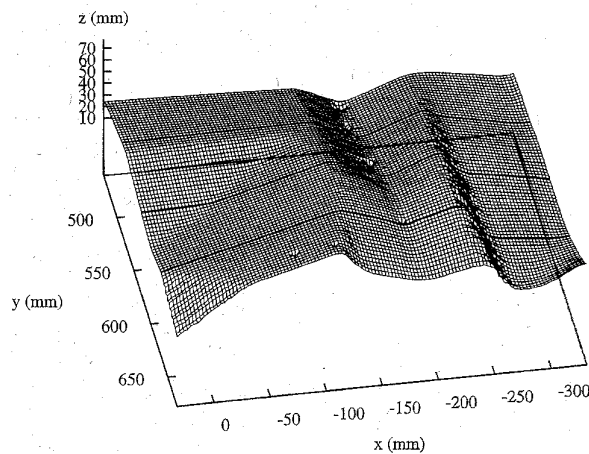


Fig. 10. The reconstructed surface using the selected digitized points.

Only 4414 points of the original grid were selected. This represented a 42.4% compression of the original digitizing points. It took 3.6 hours to redigitize these selected points. For the purpose of efficiency comparison, a dense digitizing was performed. The whole process of digitizing 10 400 points took almost 9 hours to complete.

The draw die model was digitized using the selected digitizing points. During digitizing, the LDS was posed perpendicularly to the surface according to the estimated gradients of the surface. Fig. 10 shows the result of the reconstructed surface based on these 4414 digitized data. A linear interpolation method was used to reconstruct those areas which were not digitized. One can see that the reconstructed surface is smooth. It closely represented the original model.

V. CONCLUSION

The goal of this work is to improve the efficiency and precision of the surface digitizing process. In general, computer vision has a high speed of measurement, but the result of

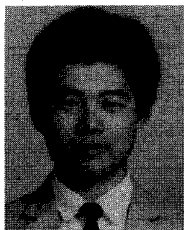
measurement has low precision. On the other hand, the LDS has a high precision but needs a long time to complete the digitizing process. In addition, the LDS has to be perpendicular or nearly perpendicular to the surface to obtain a precise result of measurement. Integration of these two sensors becomes a favorable approach to improve both efficiency and precision.

A set of rules determining the digitizing distance for the LDS was presented. By applying a 3×3 mask to the surface, the curvature information can be found using the gradient information provided by the photometric stereo approach. Based on the curvature information in each 3×3 mask, the digitizing points can be selected. The advantage of this approach is that an efficient digitizing process can be achieved while the precision of the LDS is still maintained.

In the experiment, a GM draw die model was digitized to verify this new approach. A photometric stereo approach was used to calculate the unit normal vectors of the surface, and the curvatures were obtained by making use of these normals. The rules of selection were then applied to select the digitizing points. A significant improvement in the speed of digitizing was achieved.

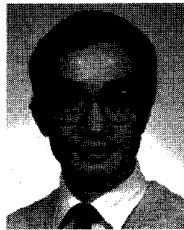
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