

# **A New Method for Measuring Perforated Surface by Coordinate Measuring Machine (CMM)**

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**Abstract:** Nowadays CMM machines are widely used in surface measurement and inspection. As inspection results from CMM machine are obtained by the means of measuring surfaces with direct contact, they are more precise than non-contact method (like optical measurement). Although, CMM machines give more reliable and accurate results rather than non-contact methods, these results come with error when outer surface contains porosity spaces. This paper proposes a new method for measuring outer surface of porous objects. In this method the probe will be located above the porous area and does not enter inside. The proposed strategy could be utilized whether CAD model of object is available or not. If CAD drawing of object exists, the probing stylus will not enter into the hole. On the other hand, if the CAD drawing does not exist, a perpendicular plane to the surface will be virtually modeled and by this normal plane the outer surface of the object will be estimated. In addition in this research an effort has been made to reduce dependence on CAD drawing.

**Keywords:** CMM, Perforated surface, Reverse engineering, Surface inspection

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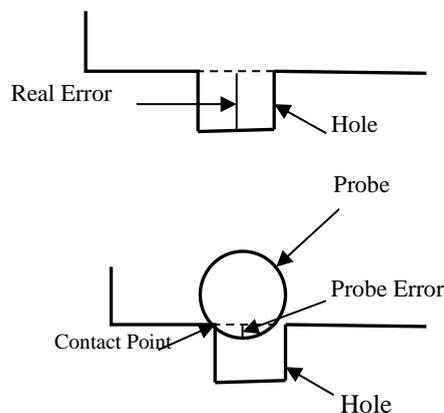
## 1 INTRODUCTION

This Reverse engineering refers to measuring geometrical properties of an object and creating 3D model of the object by the means of points cloud. This method is widely used in design and engineering phase of various industries like automobile manufacturing, aerospace, medical devices and information technology. In overall view coordinate measuring machines are categorized in four categories [1]:

- Bridge
- Cantilever or Horizontal Arm
- Gantry
- Portable

In the first step of reverse engineering a 3D model of an object should be obtained with contact and non-contact methods. Employing each of these methods has its advantages and disadvantages which are discussed sufficiently in previous studies [2]. Mechanical contact probes are the most common probes for CMM inspection. Nowadays most of CMM equipments are designed for point to point measurement. [3]. One of the most significant research which was conducted in this field was done by Lin [4] in order to proposed a model to avoid any unintended accident between probe and object. Optimization of object inspection by CMM probe has been performed by Genetic Algorithm in another research [5]. In other research a method for positioning probe by dividing object surfaces into several parts has been proposed for stylus movement over complex parts [6].

In non-contact method for measuring surfaces, as like as optical methods, more parameters should be considered. It is noteworthy that this method is based on triangular measurement principals [7]. For this purpose “Zhi” and “Sho” [8] proposed a method for an object surface scan by a laser sensor in which laser sensor has been optimized to cover a larger area. Full access to a crack while using CMM was evaluated by mathematical calculations [9]. A reversed engineered cam shaft shows acceptable results in a diesel engine test, comparing to an original cam shaft. This comparison shows reliability of reverse engineering [10]. As shown in Fig. 1, while using surface measurement equipments, there is also a probability of entering probe into perforated areas. Perforated surfaces modelling are widely required in different industries. For example in medical applications many prosthesis are made from porous materials [11, 12].



**Fig. 1** Error in measurement as the existence of porosity

In oil and gas industry many shell and tube heat exchangers contains perforated plates (Fig. 2). In these cases there is a need to create a detailed model from object surface to determine appropriate probe positioning [13]. If the read data from object surface is infected by porosity structures, final model will not be reliable and could not be used for predetermined application. The basis of contact CMM probe is contacting between probe head and the object surface and the contact point is registered as the object point. However laser sensors are operating considerably faster than contact sensors but contact sensors are more precise than optical sensors [1]. Another disadvantage of optical sensors is that when light beam enters the porosity area, this area is regarded as outer surface of object, therefore optical sensors are not recommended for porous objects.



**Fig. 2** Perforated plates used in heat exchanges

But in contact method, inner surface of porous area are not monitored as external surface except if any complex geometry exists. Error in outer surface measurement of a subject is dependent on the stylus diameter which touch surface. With increment in probe diameter, its volume which enters the porous area reduces. As it is obvious in Fig. 3, probe (1) diameter is smaller than the probe (2) diameter.

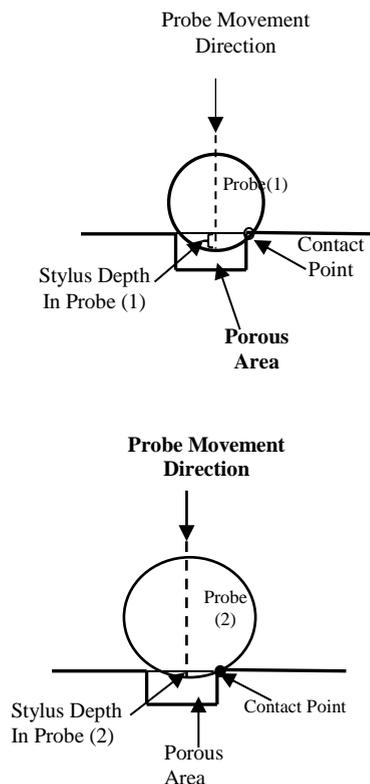


Fig. 3 Mapping nonlinear data to a higher dimensional feature space

The main purpose of this paper is to locate probe on external surface of porous object by porosity recognition in probing direction. In this method, outer surface of the object is directly measured and obtained points are from measured points regardless of surface porosities.

## 2 ILLUSTRATION OF THE NEW WORK

CMM applications in surface measurement and inspection are repeatedly studied [14, 15]. However the effect of porous surface on contact probe is less than non-contact probe, but in formable objects it shall be taken into consideration. As shown in Fig. 4, any deviation in measurement direction as a result of undetermined normal direction in goal point will be

resulted in inappropriate data gathering by machine [16].

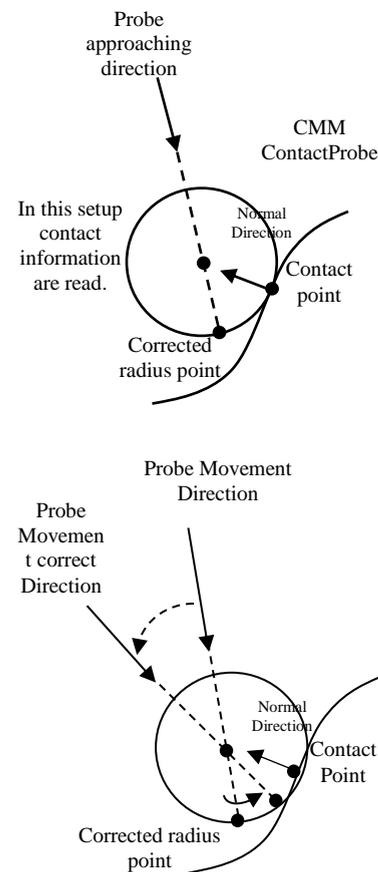


Fig. 4 Error originated from radius correction result

Therefore determination of profile surface normal direction is required for external surface measurement by CMM. If CAD model of object is available, the normal direction of external surface is also available so measurement will be done according to CAD model. For those objects which have no CAD model, normal direction will be gained by entering and exiting probe into porosity areas and using a try and error cycle. Proposed method has capability of operation whether CAD model exist or not. If CAD model exists, then normal direction will be determined and probe will move in external surface normal direction. In the case that CAD model does not exist, then external surface will be modelled approximately and this model will be modified through a try and error cycle.

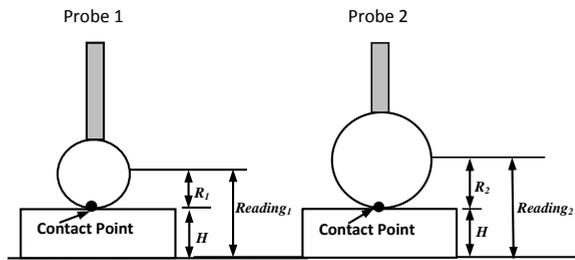
## 3 SURFACE MEASUREMENT WITH CAD MODEL

In this approach, points gathered from CAD model will be used for probe navigation and with this procedure,

porous area could be detected in any location. If any porosity exists, probe stylus will be located over it otherwise it continues to its movement according to CAD drawing.

#### 4 POROSITY RECOGNITION

To determine if the current probe location is porous or not, two probe styluses with different diameter will externally surface in normal direction respectively. This procedure starts with a probe (no. 1) which its diameter is larger than porous and continues with larger probe (no. 2) in normal direction.

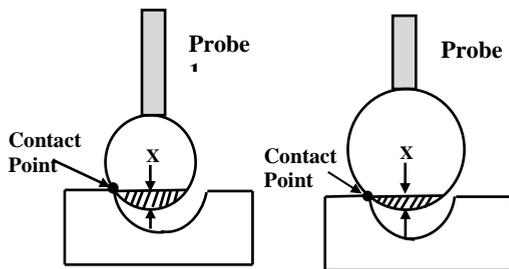


**H:** Contact Point Elevation in Normal Direction read by CMM from center

**Reading<sub>i</sub>:** Probe

**R<sub>i</sub>:**(*i*=1,2) *i* Probe Radius

Fig. 5 Two probes for a external point measurement



$R_1 < R_2$  (Radius)

$X_1 < X_2$  (Penetration)

Fig. 6 Penetration and probe radius

First of all, CMM machines record centre points of two probes and if probe has touched external surface point, the recorded data for these two points will be equal. In this case, it could be concluded that this surface is smooth and there is no porosity exist over it. As shown

in Fig. 6 the probe spherical head enters porous area partially and the volume of probe which enters depends on stylus diameter.

#### 5 POROSITY COMPENSATION

Considering flowchart in Fig. 7 we should employ following relations for porous area compensation for stylus No. *i*.

$$L_i = R_i - \sqrt{R_i^2 - d^2} \quad (1)$$

$$L_i = H + R_i - \text{Reading}_i \quad (2)$$

By considering above equations we will have:

$$R_i - \sqrt{R_i^2 - d^2} = H + R_i - \text{Reading}_i \quad (3)$$

Where;  $L_i$ :  $i^{\text{th}}$

Where  $L_i$  is probe (*i*) protrusion,  $R_i$  is stylus radius,  $d$  is vertical distance between stylus and contact point and Reading I is recorded data by CMM machine. Considering Eq. (3) for probe (1) and probe (2) we will gain Eq. 4 and 5.

$$R_1 - \sqrt{R_1^2 - d^2} = H + R_1 - \text{Reading}_1 \quad (4)$$

$$R_2 - \sqrt{R_2^2 - d^2} = H + R_2 - \text{Reading}_2 \quad (5)$$

$d$  and  $H$  are obtained from Eq. (4) and (5). The value of  $d$  could be both negative and positive as the probe could move forward or backward. As mentioned before, if recorded values are equal or:

$$\text{Reading}_1 - R_1 = \text{Reading}_2 - R_2 \quad (6)$$

Then the sensed point belongs to external surface.

#### 6 MIN. DIFFERENCE BETWEEN PROBE RADIUS

CMM resolution means minimum elevation differentiates which CMM could sense [19]. Below relation could be considered for  $R_1$  and  $R_2$ .

$$R_2 = R_1 + dR \quad (7)$$

Eq. (3) is rewritten as below after removing indices:

$$R - \sqrt{R^2 - d^2} = H + R - \text{Reading} \quad (8)$$

By derivation from Reading to  $R$ , following equation will be reached:

$$\frac{d\text{Reading}}{dR} = \frac{R}{\sqrt{R^2 - d^2}} \quad (9)$$

$$d\text{Reading} = \frac{R \times dR}{\sqrt{R^2 - d^2}} \quad (10)$$

For this reason CMM recorded data shall be of higher precision than CMM resolution:

$$dReading > Resolution \tag{11}$$

$$\frac{R \times dR}{\sqrt{R^2 - d^2}} > Resolution \tag{12}$$

$$dR > \frac{Resolution \times \sqrt{R^2 - d^2}}{R} \tag{13}$$

As the values of d is equal to Zero and  $dR > Resolution$ , the probe radius difference for obtaining compensation distance d shall be greater than CMM resolution. This procedure is shown in Fig. 7.

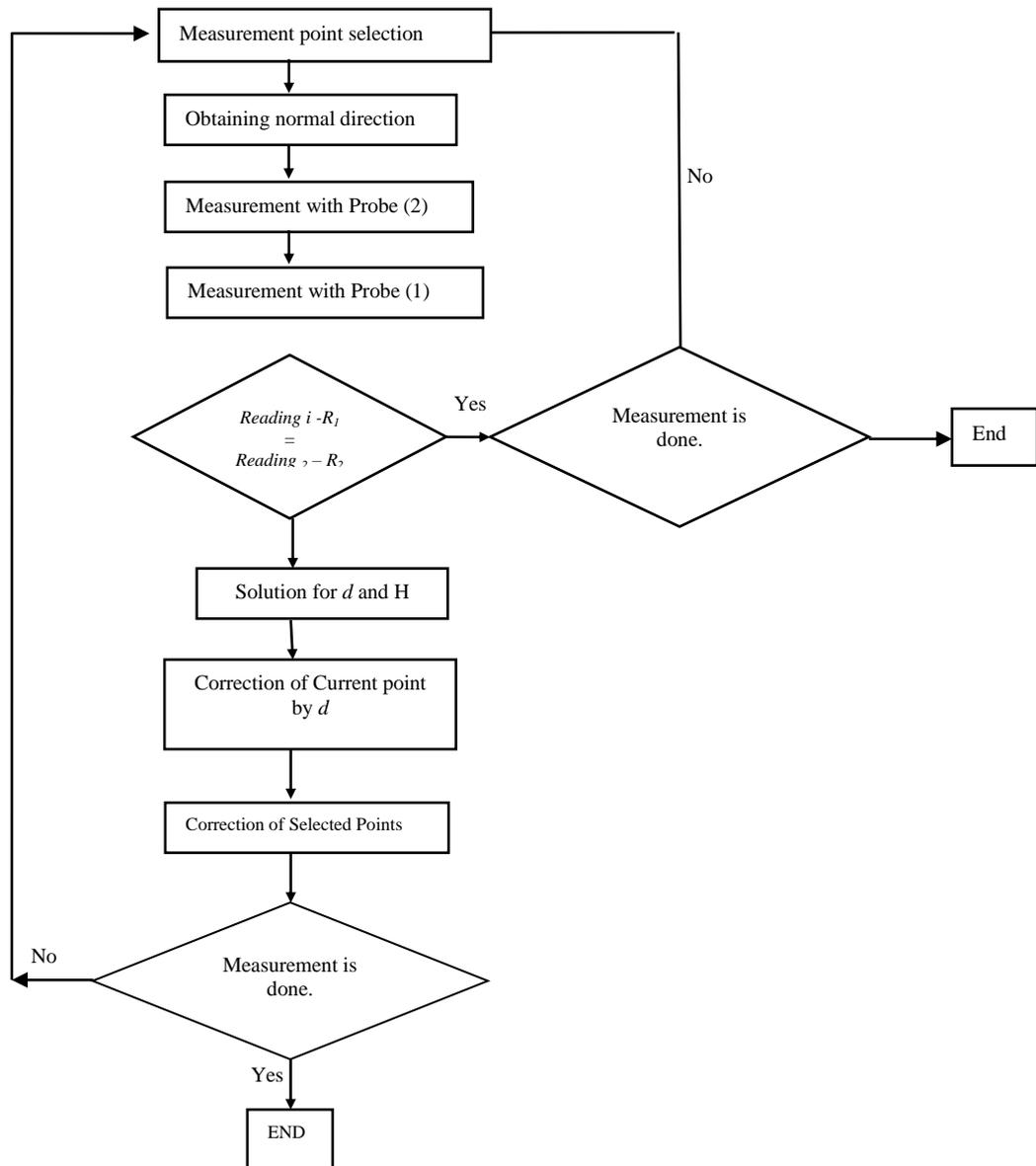


Fig. 7 Flowchart for Measurement by using CAD model

## 7 MEASUREMENT WITHOUT CAD MODEL

The main difference between this model and previous one is unavailability of CAD model and consequently impossibility of providing normal direction to surface. In this method, a primary model of object which was approximated previously by touching some parts of object is used for normal direction calculation and after that this direction will be corrected in a try and error cycle. First of all, three points will be chosen and then a function will be fitted to these points. Normal direction will be gained from this function. If  $H_{i-2}(x_{i-2} - z_{i-2})$ ,  $H_{i-1}(x_{i-1} - z_{i-1})$  and  $H_i(x_i - z_i)$  are three consecutive points and  $H_i(x_i - z_i)$  is the last one (Fig. 8) the following equations will define the fitted function:

$$S_{i-2}(x) = a_{i-2}(x - x_{i-2})^3 + b_{i-2}(x - x_{i-2})^2 + c_{i-2}(x - x_{i-2}) + d_{i-2}, x \in [x_{i-2}, x_{i-1}] \quad (14)$$

$$S_{i-1}(x) = a_{i-1}(x - x_{i-1})^3 + b_{i-1}(x - x_{i-1})^2 + c_{i-1}(x - x_{i-1}) + d_{i-1}, x \in [x_{i-1}, x_i] \quad (15)$$

Slope of send part is:

$$\frac{dS_{i-1}(x)}{dx} = 3a_{i-1}(x - x_{i-1})^2 + 2b_{i-1}(x - x_{i-1}) + c_{i-1}, x \in [x_{i-1}, x_i] \quad (16)$$

For  $x = x_i$  slope is equal to:

$$\frac{dS_{i-1}(x_i)}{dx} = 3a_{i-1}(x_i - x_{i-1})^2 + 2b_{i-1}(x_i - x_{i-1}) + c_{i-1} \quad (17)$$

Variations  $P_{i-2}$ ,  $P_{i-1}$ ,  $Q_{i-2}$  and  $Q_{i-1}$  are defined as below:

$$\begin{bmatrix} P_{i-2} \\ Q_{i-1} \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \times \begin{bmatrix} x_{i-2} \\ x_{i-1} \\ x_i \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} Q_{i-2} \\ Q_{i-1} \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \times \begin{bmatrix} z_{i-2} \\ z_{i-1} \\ z_i \end{bmatrix} \quad (19)$$

After using all boundary conditions,  $a_{i-1}$ ,  $b_{i-1}$  and  $c_{i-1}$  will be resulted.

$$a_{i-1} = \frac{(Q_{i-2}P_{i-1} - Q_{i-1}P_{i-2})}{[2P_{i-1}^2P_{i-2}(P_{i-1} + P_{i-2})]} \quad (20)$$

$$b_{i-1} = 3 \times \frac{(Q_{i-1}P_{i-2} - Q_{i-2}P_{i-1})}{[2P_{i-1}P_{i-2}(P_{i-1} + P_{i-2})]} \quad (21)$$

$$c_{i-1} = \frac{(Q_{i-1}P_{i-2} - Q_{i-2}P_{i-1})}{P_{i-1}(P_{i-1} + P_{i-2})} + \frac{Q_{i-2}}{P_{i-2}} \quad (22)$$

Therefore slope in  $x = x_i$  will be gained by following equation.

$$\frac{dS_{i-1}(x_i)}{dx} = \frac{Q_{i-1}P_{i-2}(3P_{i-1} + 2Q_{i-2}) - Q_{i-2}P_{i-1}^2}{2P_{i-1}P_{i-1}(P_{i-1} + P_{i-2})} \quad (23)$$

## 8 CORRECTING THE NORMAL DIRECTION

As the cubic spline interpolated in  $x = x_i$ , normal direction slope in interpolated line is:

$$\frac{-1}{\frac{dS_{i-1}(x_i)}{dx}} = \frac{2P_{i-1}P_{i-2}(P_{i-1} + P_{i-2})}{Q_{i-2}P_{i-1}^2 - Q_{i-1}P_{i-2}(3P_{i-1} + 2Q_{i-2})} \quad (24)$$

However interpolated line shows overall direction of curve but also it does not completely match on curve therefore curve normal line is deviate from real normal line. As shown in Fig. 8, real curve is located under interpolate line but in real case it is located over interpolated line. As shown in Fig. 10, it is obvious that  $O_1$  is the approximated stylus center in a distance equal to probe diameter from approximated measured point in normal direction.  $O_2$  is the real position of probe stylus when it touches real curve.

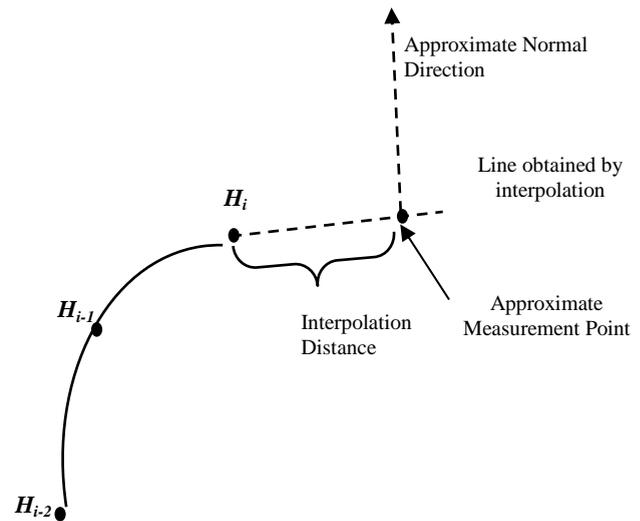


Fig. 8 Cubic spline interpolation

For determining compensating angle  $\alpha$  in approximated normal direction, the distance between  $O_1$  and  $O_2$  or  $\overline{O_1O_2}$  is required. We presume that this distance is an interpolated distance therefore compensating angle  $\alpha$  is obtained as below:

$$\tan(\alpha) = \frac{\overline{O_1O_2}}{Distance} \quad (25)$$

$$\alpha = \tan^{-1}\left(\frac{\overline{O_1O_2}}{Distance}\right) \quad (26)$$

$\alpha$  is used for correction of normal direction calculation. As the approximated normal direction and interpolated line are perpendicular, both of them will rotate as much as  $\alpha$ .

Therefore approximated measure point and O1 will change. Point O1 will be positioned in a distance equal to probe diameter from new measured point in normal direction. As  $\alpha$  is approximately calculated from equation (6), probe stylus will change its movement in normal direction and continue to this action till value of  $\alpha$  reaches to the predetermined value which was set by user. When normal direction is corrected, two probing styluses approach to surface for measurement 5 consequently. Then compensation distance d will be calculated and by this distance of approximated, measured point from interpolated line will move forward or backward. In this case if any point could satisfy following condition it will be regarded as an external point:

$$\text{Reading}_1 - R_1 = \text{Reading}_2 - R_2 \tag{27}$$

Fig. 10 represents real curve under interpolated line. When real curve is located above the interpolated line, normal direction correction will be like this except when  $\overline{O_1O_2}$  distance chooses a value smaller than zero and in this case compensation angle  $\alpha$  will be positive. Regarding the discussion in this section, when CAD model is not available, all the procedure which is shown in Fig. 11 shall be done.

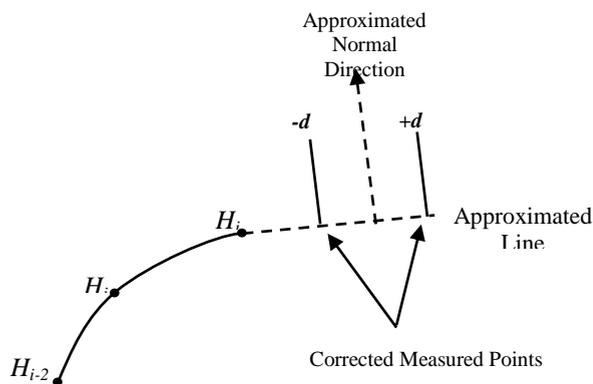


Fig. 9 Corrected Measured Points

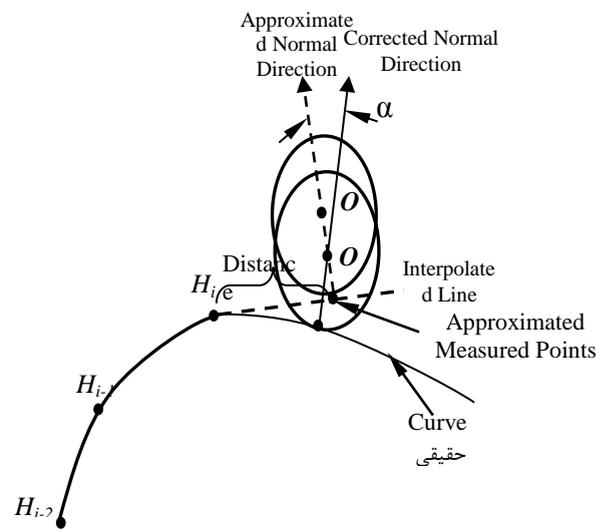


Fig. 10 Corrected Normal Direction

Table 1 corrected and approximated normal directions

	Corrected Normal Direction			Approximated Normal Direction			ROTATION Angle (Degree)
	k	j	i	k	j	i	
point 1	-0.38938	0	0.88663	-0.62002	0	0.77482	-13.47033
point 2	-0.78548	0	0.56635	0.49181	0	0.86257	21.83183
point 3	-0.88757	0	0.38723	-0.90740	0	0.39744	0.00000
point 4	-0.95830	0	0.13920	-0.92161	0	0.36296	11.76009
point 5	-0.96127	0	-0.11701	-0.98904	0	0.04356	8.45004
point 6	-0.92426	0	-0.28893	-0.97188	0	-0.18930	5.70398
point 7	-0.86331	0	-0.43867	-0.93113	0	-0.33761	6.32797
point 8	-0.76683	0	-0.59136	-0.86467	0	-0.48400	7.59559
point 9	-0.69285	0	-0.67653	-0.76044	0	-0.63638	4.02633
point 10	-0.79955	0	-0.54630	-0.69461	0	-0.70819	-9.92265
point 11	-0.89317	0	-0.37414	-0.83626	0	-0.53195	-8.60936
point 12	-0.96675	0	-0.05592	-0.91431	0	-0.38114	-17.19924
point 13	-0.92046	0	0.30082	-0.98653	0	-0.83082	-11.89288

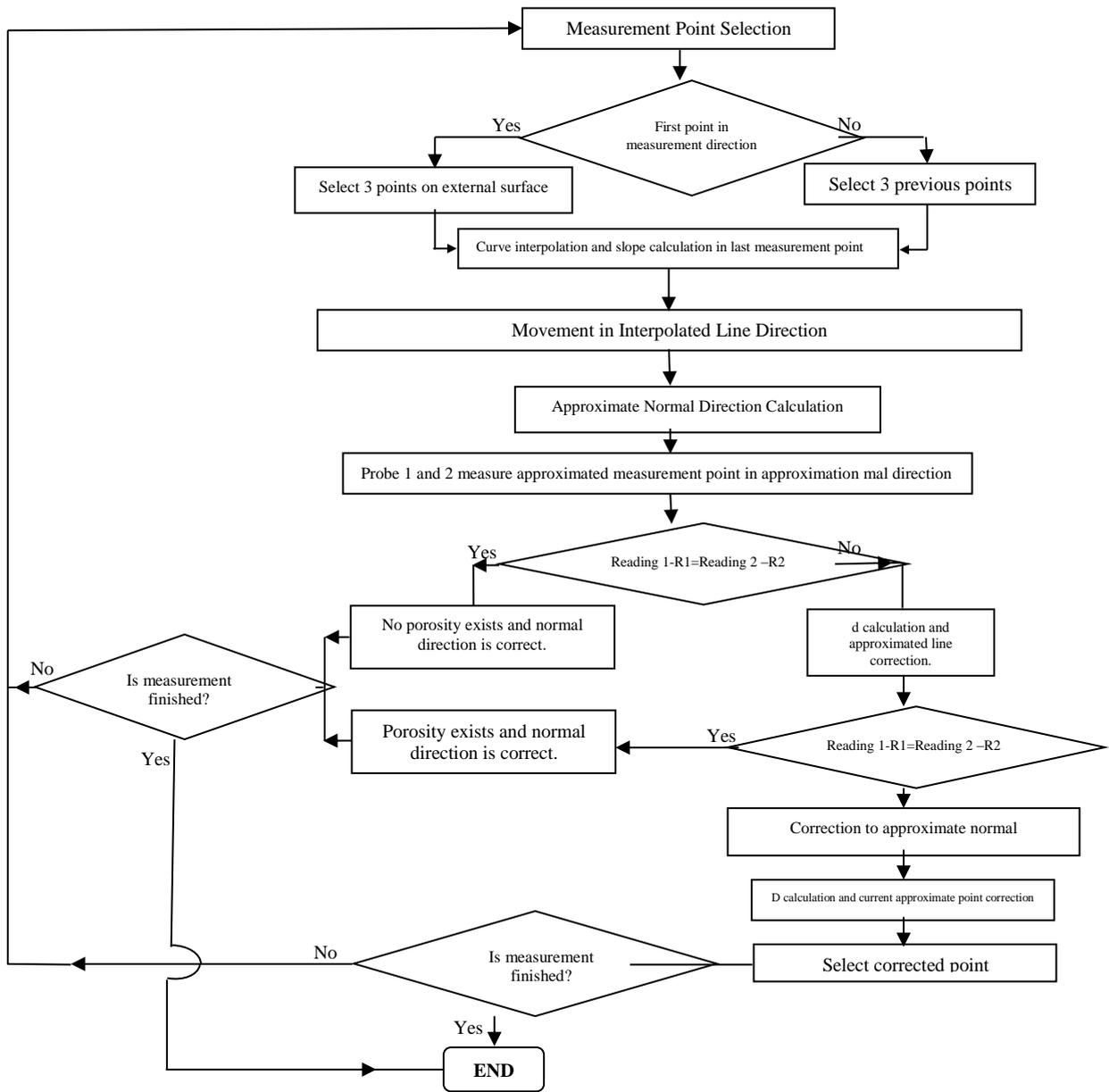


Fig. 11 The measurement flowchart without CAD model

## 9 IMPLEMENTATION

The implementation of this method has been done on a CMM machine, manufactured by Mitutoyo, and a specimen which was a perforated steel plate. This plate was perforated with holes, 0.075 mm center to center distance. The specimen was measured by a 2mm probe. Table (1) shows primary measured points by interpolation and corrected measured points. As the CAD model is not available, normal direction first are approximated and then will be corrected.

## 10 CONCLUSION

In this paper a new method has been proposed to avoid porosity spaces in external surface measurement by coordinate measurement machine (CMM). This method is capable to be utilized whether CAD model is available or not. When CAD model is available the probe will approach to object in normal direction but when CAD model does not exist the normal direction will be estimated by compensation and then external surfaces will be measured. The result of this method is

compared with results of measurement without compensation and this comparison shows a considerable increment in measurement accuracy. The future researches could be conducted in measuring the external surfaces with different porosities and different shapes.

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