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Development of 5-Axis Microscribe System for Off-Line Buffing Robot Path Programming and Its Application

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버핑 로봇의 오프라인 경로 프로그래밍용 5축 마이크로스크라이브 개발 및 응용

노태정[1*]

Abstract We propose how to program the off-line buffing robot path along shoes' outsole shape in the footwear buffing process by a 5-axis microscribe system like robot mechanism. The microscribe system we developed consists of a 5-axis robot link with a turn table, a signal processing unit, PC and an application software program. Itmakes a robot path on the shoes' upper in accordance with the movement of a microscribe with many joints. The developed system calculates the encoder pulse values for the microscribe arm's rotation and transmits the angle pulse values to the PC through a processing unit.
Denavit-Hartenberg's(D-H) direct kinematics is used to make the global coordinate from microscribe joint one. Problems with the microscribe's kinematics can be solved efficiently and systematically by D-H representation. With the coordinate values calculated by D-H equation, our system can draw a buffing gauge-line on the upper sole. We obtain shoes' outline points, which are 2 outlines coupled with the points and the normal vector based on the points. By applying the system to the buffing robot in a flexible manufacturing system, it can be used effectively to program the path of a real buffing robot.

Key Words: 5-axis microscribe, Denavit-Hartenberg's(D-H) direct kinematics, off-line path programming, buffing robot, buffing gauge line, outsole, footwear industry

요 약 신발 버핑공정에서 로봇 메카니즘과 같은 5축 마이크로스크라이브에 의하여 신발창 형상을 따라서 버핑 로봇 경로를 오프라인으로 프로그래밍하는 방법을 제안한다. 개발한 마이크로스크라이브 시스템은 턴테이블이 부착된 5축 로봇링크, 신호처리장치, PC 및 응용 소프트웨어 프로그램으로 구성되어 있다. 많은 조인트를 가진 마이크로스크라이브를 신발창 표면을 따라 이동시킴으로써 로봇 경로가 만들어진다. 개발시스템은 마이크로스크라이브 암의 회전에 해당되는 엔코더 펄스 값을 환산하며, 이 각도 값을 신호처리장치를 통하여 PC로 전송한다.
Denavit-Hartenberg's(D-H) 직접 키네메틱스가 마이크로스크라이브 조인트 각도 값으로서 글로벌 좌표값을 만드는데 사용된다. 마이크로스크라이브의 키네메틱스 문제는 D-H 표현에 의하여 효과적이고 시스템적으로 해결된다. 개발시스템은 D-H식에 의하여 계산된 좌표 값으로서 신발 갑피 위에 버핑 게이지 라인을 그릴 수 있으며, 또한 신발 갑피 위에 각 점들과 그 점에 수직인 벡터와 결합된 2개의 외곽 라인으로서 로봇 경로를 얻는다. 개발시스템을 FMS의 버핑 로봇에 적용함으로써 실제적인 버핑 로봇의 경로를 프로그래밍하는데 효과적으로 사용될 수 있다.

1. Introduction

In the present footwear industry, most of the manufacturing processes are done by operating machines or handwork by workers. This has led to the decline of productivity and workers'avoidance of footwear manufacturers, resulting in the stagnation of the industry in general.Among the footwear processes, the process for

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making a complete product by bonding the outsole and the upper leather together is usually done in a poor working environment and thus brings about frequent accidents. But the most significant problem comes fromthe features of shoe outsole. Since there are various kinds of shoe outsole in terms of size, shape, color, and raw materials, it is not only difficult to actively develop a system coping with this diversity, but also difficult to process in an efficient way. [1][2]

In the recent studies for developing flexible footwear manufacturing systems, off-line path programming systems have been used for the buffing and bonding process in footwear assembling facilities. The developed countries have beenmaking an effort to focus on production and innovation of items to distinguish themselves from other developing countries. Also, those developed countries intensively invest inFMS(Flexible Manufacturing System). In addition to that, to develop an innovative product, those countries try to use new scientific human technologies and environments to drive forward the innovation of products and manufactures at the same time. Therefore, it is necessary for our country to introduce FMS and an automaticfacility for producing shoes tuned forthe domestic situation. [3][4][5][6][7]

In recent years J. Y. Kim[8] proposedthe off-line robot path programming based on CAD Data in adhesive application system for shoes outsoles and uppers in footwear industry, T. J. Lho[9] proposed the off-line programming of robot path, which consists only 1 line, for footwear bonding process, and T. J. Lho[10] proposed the development of shape scanner for off-line robot path programming in footwear bonding process.

Since the buffing process is mechanically scribing, its path is required to be perpendicular to processing surface. In order to solve this problem, we measured the up and down lines. To compute the normal vector, 3 coordinates are needed. We obtained shoes' outline points, which are 2 outlines coupled with the points and the normal vector based on the points. These data are supposed to be transformed into a *.dxf* file to be used as data of buffing robot. Our system simulated a buffing gauge line by using spline curves coupled with each point from a *dxf*file in *Autocad.*

Shoe outsole buffing area is created after inputting a shape from 5-axis microscribe developed and is displayed on the screen at the same time. These entire steps constitute the processes of making automatic buffing robot's path. When a worker does the buffing job with a non-factory automation system, it has merits for the speed of processing time, but it also has demerits for accuracy. The buffing process line depends on workers' sense of responsibility and expertise.

In the system proposed in this paper, as the 5-axis link robot with the turn table moves along a processing path on the shoes' upper sole, the off-line programming system generates the processing paths of the shoe's buffing robot and transfers them to its controller.

The microscribe system configuration is described in Section 2, Denavit-Hartenberg's direct kinematics is introduced in Section 3, and the simulation results for the offline robot path programming of shoes' outsole coordinate are presented in Section 4. Finally the conclusions are summarized in Section 5.

2. Microscribe System Configuration

The system that we proposed in this paper calculates the encoder pulse values for the robot arm's rotation and transmits the angle pulse values to the PC through a circuit. Then, Denavit-Hartenberg's(D-H) direct kinematics[11][12] is used to make the global coordinate from robot joint one. The determinant is obtained with kinematics equation and D-H variable representation. To get the kinematics equation, we have to set up the standard coordinates first. Too many links and complicated structure make it difficult to solve kinematics problems in a geometrical way. Problems with the robot's kinematics can be solved efficiently and systematically by D-H representation. We can display the shape of a shoe's outsole buffing part by using the 5-axis and create the automatic buffing robot's moving coordinate by the normal vector. The configuration of our system is given in figure 1.

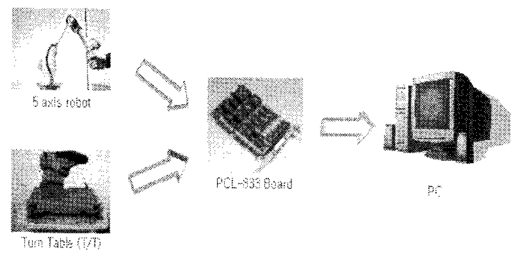


Fig. 1 Microscribe system configuration for buffing robot

Since 5-axis multi-joints microscribe digitizes a model easily and fast, complex 3-dimension data can be created in the computer if a user makes the probe track outline of an object. Fast digitizing a real object, it serves as a dialog measuring device in a 3-dimensional computer environment. Also, it has a merit that it digitizes all objects without respect to shape, size and materials. The shoe's outsole is marked by a probe of the microscribe, and the encoders' pulse values are read and counted in the *PCL-833* encoder pulse counter board from the origin point to the probe's location. Then, we can obtain the coordinate by the kinematics and display the shoe's outsole on the screen through the *C* program. At *PCL-833* encoder pulse counter, we can count in 24-bit with the 3-axis encoder counter card.

Pulses from the robot arm's encoders go to the *PCL-833* encoder pulse counter board. First, it counts the pulse numbers at the *PCL-833* encoder pulse counter board, and then transforms the counted pulse into the radian value in the program. That is, if the angle for a pulse is a known value, we can obtain the angle to the total pulse numbers. With the radian values from the pulse angles and the known link length, the last position (*i.e.*, shoe's outer point location from the origin point) can be extracted from the direct-kinematics. Then, the turn table(T/T) calculates rotation and translation coordinates from the 5-axis direct-kinematics freely rotating and marking points and radian values of *T/T* pulse. Because the shoe's outer coordinates are displayed on the screen, it is possibleto obtain the normal vector from shoe's 3 points, and then save this normal vector as a text file. The normal vector saved as a text file is used for obtaining robot's processing paths for the buffing process. Figure 2 represents the process for obtaining a coordinate of buffing gauge line, and figure 3(a) and (b) show an overview of the developed microscribe.

Read signal from robot arms (6-encoder)

↓

Transform received pulse values to radian values

↓

Calculate relative coordinates by using
Denavit-Hartenberg representation

↓

Calculate rotated and translated coordinates
By using encoder values in turn table

↓

Print out relative coordinate (.dxf, .txt, .pts)

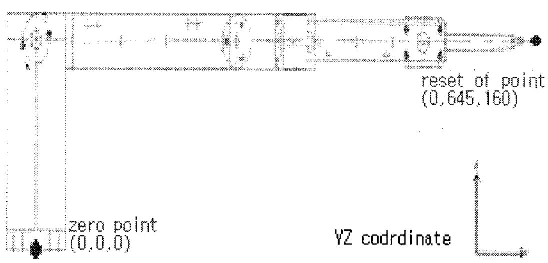
↓

Create normal vector

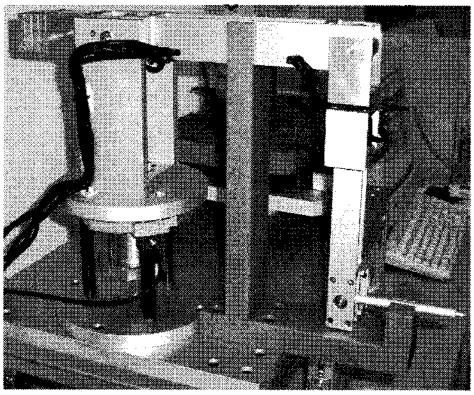
↓

Save normal vector as text file

Fig. 2 The process steps for obtaining a coordinate of buffing gauge line



(a)



(b)

Fig. 3 Overview of a microscribe with 5-axis arm developed[10]

3. Denavit-Hartenberg's Direct Kinematics

In the global coordinate (*x, y, z*)after extracting a value form the micrscribe, the determinant is obtained with kinematics equation. We have to set up the standard coordinates first. Too many links and complicated structure make it difficult to solve kinematics problems in a geometrical way. We can solve these problems with the robot's kinematics efficiently and systematically by using D-H representation. From the coordinate of 5-axis robot shown in figure 4, the D-H variables extracted from the set-up coordinate are arranged and shown in the below Table1. [11][12]

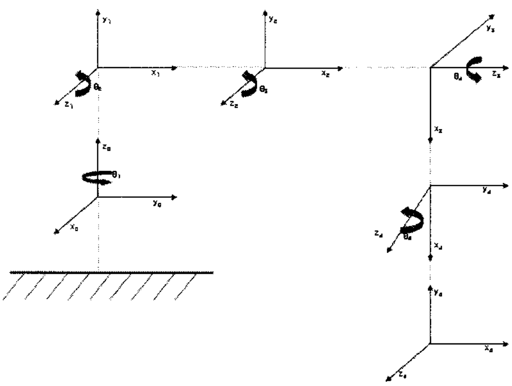


Fig. 4 Coordinate of 5-axis robot manipulator

Table 1. Denavit-Hartenberg's parameters of each axis.

Link	θ_i	d_i	α_i	a_i
A_1	θ_1*	d_1	$\pi/2$	0
A_2	θ_2*	0	0	a_2
A_3	θ_3*	0	$-\pi/2$	0
A_4	θ_4*	d_4	$\pi/2$	0
A_5	θ_5*	0	0	a_5

To solve all kinematics, we can set up a coordinate at each link as we please. To effectively solve kinematics, however, it is useful to set up a well organized coordinate. The most frequently used way is D-H representation. We can obtain the global coordinates by transforming pulse numbers to values and calculating. The below determinant is the 5-axis robot's calculation in the direct kinematics. Each link matrix is obtained byinputting the variables in Table 1 to the below determinant.

By D-H representation, homogeneous transform A_i is transformed into multiplication of 4 normal transform matrices.[9] [10][13]

$$A_i = Rot_{z,\theta i}\ Trans_{z,di}\ Trans_{x,ai}\ Rot_{x,ai}$$

$$= \begin{pmatrix} C\theta_i & -S\theta_i & S\theta_i Sa_i & a_i C\theta_i \\ S\theta_i & C\theta_i Ca_i & -C\theta_i Sa_i & a_i S\theta_i \\ 0 & Sa_i & Ca_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

$$A_0^5 = A_1 A_2\ A_3\ A_4\ A_5 \quad (2)$$

Where C is a *cosine* function and S is a *sine* function. The obtained 4x4 homogeneous transformation matrices are shown below, which indicates the relative location and direction of set-up coordinates $\{i\}$ and $\{i+1\}$.

$$A_0^5 = \begin{pmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

Where,

$$
\begin{aligned}
r_{11} &= C_5(C_1C_{23}C_4 - S_1S_4) - C_1S_{23}S_5 \\
r_{12} &= -S_5(C_1C_{23}C_4 - S_1S_4) - C_1S_{23}S_5 \\
r_{13} &= C_1C_{23}S_4 + S_1C_4 \\
r_{21} &= C_5(S_1C_{23}C_4 + C_1S_4) - S_1S_{23}S_5 \\
r_{22} &= -S_5(S_1C_{23}C_4 + C_1S_4) - S_1S_{23}S_5 \\
r_{23} &= S_1C_{23}S_4 - C_1C_4 \\
r_{31} &= C_4S_{23}C_5 + C_{23}S_5 \\
r_{32} &= -C_4S_{23}C_5 + C_{23}C_5 \\
r_{33} &= S_{23}S_4
\end{aligned} \tag{4}
$$

and

$$
\begin{aligned}
p_x &= a_5a_{00} - C_1S_{23}d_4 + C_1C_2a_2 \\
p_y &= a_5a_{10} - S_1S_{23}d_4 + S_1C_2a_2 \\
p_z &= a_5a_{20} - C_{23}d_4 + a_2S_2 + d_1 \\
a_{00} &= C_5(C_1C_{23}C_4 - S_1S_4) - C_1S_{23}S_5 \\
a_{10} &= C_5(S_1C_{23}C_4 + C_1S_4) - S_1S_{23}S_5 \\
a_{20} &= C_4S_{23}C_5 + C_{23}S_5
\end{aligned} \tag{5}
$$

We also describe how to display a shoe's shape followed by the direction of the turn table. The reason for the rotation of the *T/T*is that it is difficult for a robot arm to measure when a long-length shoe outsole or a big item is measured. By using the *T/T*, we can not only have more space, but also obtain more accurate points through rotating the *T/T* as 90° or 180°. As shown in figure 5, first, move in parallel to overlap the *T/T's*axes and a robot arm's axes. Then, rotate as much as assigned, and the axis is moved parallel back to the origin position

$$
(x' \; y' \; z' \; 1) = (x \; y \; z \; 1) \tag{6}
$$

$$
\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ a-0 & b-0 & c-0 & 1 \end{pmatrix}
\begin{pmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}
\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0-a & 0-b & 0-c & 1 \end{pmatrix}
$$

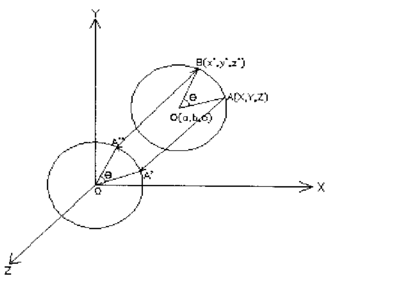


Fig. 5 Transformation of turn table rotation

4. Simulation results for the off-line robot path programmingand application to buffing robot

A drawing of the shoe's outsole is necessary to draw the outline of the shoe's outsole with *AutoCAD* or *CATIA*. But if we use the 5-axis robot, we can draw the outline of the shoe's outsole without the drawing of the shoe's outsole. We can cover how the automatic buffing robot finds the shoe-buffing paths based on the shape as in figure 6.

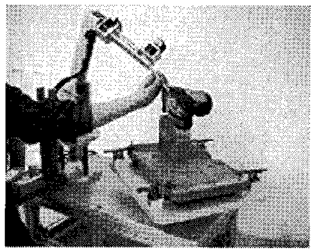


Fig. 6 Overview for working by microscribe

As a shoe fixed on the *T/T*are rotated and is measured by a 5-axis robot moving along the outline of the shoe, 6 encoder values are saved into a PC memory through *PCL-833* encoder pulse counter board. The saved encoder values are transformed into degree from radian and calculated for 3-dimensional coordinates (*x*, *y*, *z*) by the D-H representation, and the obtained coordinates are displayed on the screen as a shoe's winding shape itself. Figure 7 shows the process to display a real shoe outsole shape fixed on the *T/T*. With the obtained coordinates through Figure 6, there is a coordinate extraction program for a shoe shape in Figure 7.

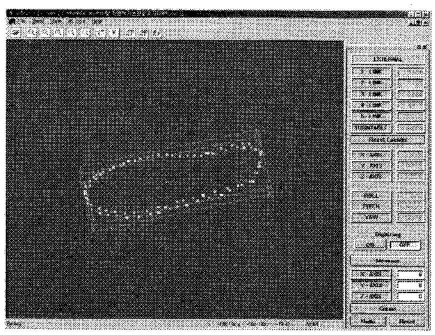


Fig. 7 Creation for the buffing gauge lines

The probe of microscribe pointed around 80 points along a buffing outline. In order toobtain the normal vector, we measured the up and down lines. To compute the normal vector, 3 coordinates are needed. The probe has to point out along the up and down lines to have the normal vector at each point on the two lines.

These points are saved as a *txt*file to compute the normal vector through a normal vector generator. What the normal vector generator program does is that it first reads previously marked points, creates the normal vector, throws away the first point, re-reads a new point, and creates the normal vector. It generates each normal vector at each point until it reaches the saved last point. Table 2 shows each point's coordinate of a shoe outline as a text file. There is a generated file in the form of the vector from the text file in Table 3. In this file, the location of a point is shown as '*mm*' unit from the origin of the robot arm. That is, the robot arm's initial state is (x, y, z) = (0, 0, 0), and from the initial state, it shows point coordinates for a shoe outsole. It helps to figure out that a present coordinate is correctly marked.

Table 2. Text file of points coordinate

```
0
SECTION
2
ENTITIES
0
POINT
5
0
8
0
10
-431.440
20
-68.860
30
183.670
 .
 .
-427.660
20
-64.260
30
174.400
0
ENDSEC
0
EOF
```

Table 3. Text file of normal vector

-431.440	-68.860	183.670
-431.530	-68.960	184.140
-428.080	-43.850	178.660
-425.010	-23.790	179.220
-425.180	-12.030	192.130
-419.530	-7.080	179.720
-419.890	5.810	190.170
-416.340	12.110	179.220
-415.400	46.960	172.660
-414.250	45.940	172.680
-416.800	58.590	168.440
-416.190	58.050	168.030
-419.990	69.190	176.160
.		
.		
-424.420	-114.580	175.720
-424.420	-114.580	175.720
-431.340	-105.350	184.600
-424.490	-99.660	175.300
-431.760	-89.030	182.000
-424.820	-83.170	173.840
-423.520	-83.440	174.290
-432.230	-71.010	181.240
-427.460	-65.070	174.830
-427.660	-64.260	174.400

Table 4. dxffile of points

-0.981	0.098	-0.167
0.987	-0.149	-0.063
0.976	-0.154	0.153
-0.907	0.306	-0.291
0.916	-0.236	0.323
-0.962	0.154	-0.223
0.944	0.036	0.327
-0.142	-0.179	-0.973
0.301	0.357	0.884
-0.715	-0.347	-0.606
0.030	-0.582	0.812
-0.964	-0.227	-0.140
0.987	0.126	0.103
	.	
	.	
-0.339	-0.590	0.733
0.729	0.619	-0.294
0.674	0.338	0.657
-0.799	-0.021	-0.601
0.763	0.121	0.636
-0.733	-0.075	-0.677
0.026	-0.822	-0.568
-0.367	-0.636	0.678
-0.730	-0.137	-0.670
0.400	0.505	0.765

We obtain shoes outline points, 2 outlines coupled with the points, and the normal vector based on the points. These data are supposed to be transformed into a *.dxf* file to be used as data of automatic buffing robot. As shown in figure 8, this system developed simulates a buffing gauge line by using spline curves coupled with each point from *dxf* file in *Autocad* in Table 4.

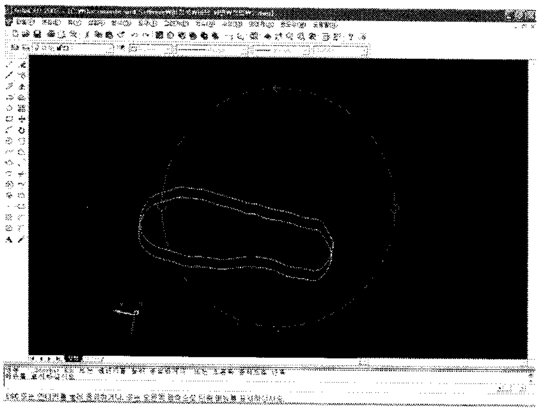


Fig. 8 3-dimensional shoe outsole

Figure 9 shows how the normal vectors of a shoe outsole are saved into a robot and applied to a buffing robot in the shoe product line

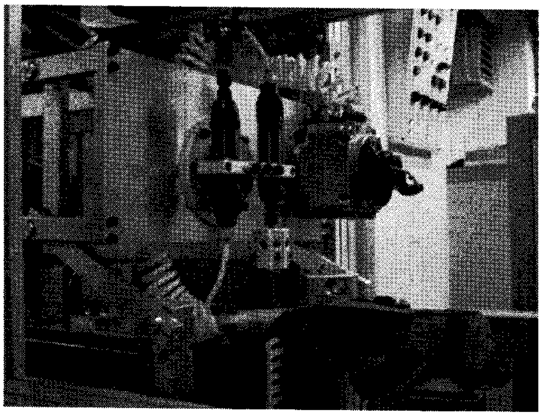


Fig. 9 Application to the buffing robot

5. Conclusion

In this paper, a method for obtaining robot paths for automatic buffing process has been proposed. Shoe outsole buffingarea is created after inputting a shape from 5-axis microscribe developed and is displayed on the screen at the same time. These entire steps constitute the processes of making automatic buffing robot's path. The system proposed in this paper deals with a stage of shoe factory automation, and is expected to reduce labor costs and to improve the quality of products. It helps to improve the automation process of shoe industry, thus contributing to the improvement of productivity. The following conclusions are summarized.

(1) The microscribe system we developed consists of a 5-axis robot link with a turn table, a signal processing unit, PC and an application software program. It makes a robot path on the shoes' upper in accordance with the movement of a microscribe with many joints. In so doing, it first reads 5 encoders' pulse values while the microscribearm points a shoes' outsole shape from the initial status. The developed system calculates the encoder pulse values for the microscribe arm's rotation and transmits the angle pulse values to the PC through a processing unit.

(2) Then, Denavit-Hartenberg's(D-H) direct kinematics was used to make the global coordinate from microscribe joint one. The determinant was obtained by the kinematics equation and D-H variable representation. To drive the kinematics equation, we have to set up the standard coordinates first. Too many links and complicated structure make it difficult to solve kinematics problems in a geometrical way. Problems with the microscribe's kinematics can be solved efficiently and systematically by D-H representation. Finally, with the coordinate values calculated by D-H equation, our system can draw a buffing gauge-line on the upper sole. Also, it can program off-line robot path on the shoes' upper.

(3) We obtained shoes' outline points, which are 2 outlines coupled with the points and the normal vector based on the points. These data are supposed to be transformed into a *.dxf* file to be used as data of buffing robot. Our system simulated a buffing gauge line by using spline curves coupled with each point from a *dxf* file in *Autocad.* By applying the system to the buffing robot in a flexible manufacturing system, it was used effectively to program the path of a real buffing robot.

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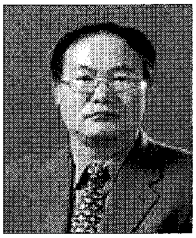

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