

**A study on Development of Footwear Shape Scanner for Off-Line
Robot Path Programming**

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Abstract: We need a lot of manpower and we can cut down a labor cost by applying industrial robots the footwear bonding automation process. In this study, we suggest how to program off-line robot path along a shoe's outsole shape in the footwear bonding process by 5-axis microscribe system like robot arms.

This microscribe system development consists 5-axis microscribe mechanics, signal processing circuit, and PC with software. It is the system for making database of a shoe's outsole through the movement of a microscribe with many joints. To do this, first read 5-encoders' pulse values while a robot arm points a shoe's outsole shape from the initial status. Then, calculate a relative shoe's outsole by Denavit-Hatenberg's (D-H) direct Kinematics of known length of links and coordinate values. Next, calculate the encoders' pulse values of the robot arm's rotation and transmitting the angle pulse values to the PC through a circuit.

Finally, it is able to display a shoe's outsole at real-time by computing the Denavit-Hantenberg's (D-H) direct kinematics in the PC. With the coordinate values calculated above, we can draw a bonding gauge-line on the upper. Also, we can make off-line robot path programming compute a shoe's bonding area on the upper. These results will be effectively applied for programming a robot path on off-line and automatically.

Keywords: off-line robot path programming, footwear shape scanner, 5-axis microscribe system, Denavit-Hatenberg's (D-H) direct kinematics

1. INTRODUCTION

When we make a product based on a certain shape, a computer is the most suitable device to make experiments in various ways and to do a simulation. To use a computer, we should build a database of the shape, make the database as a file, and configuration.

The subjection of this study is to develop these steps systematically. To construct a database of a shape, a 5-axis robot arm and a 6-axis rotation plate are needed. When the 5-axis robot places the outside point of a shoe, we are able to obtain the robot arm's global coordinate (x, y, z) by using the five encoders' values in the 5-axis robot arm and the known lengths of the links with the direct kinematics approach. To calculate the accurate global coordinate, the minuteness of the direct kinematics calculation and the robot arm should be highly required, which can make the less error rate. A signal processing circuit, designed to read pulse values of the robot arm's rotation, transmits the angle pulse values to the PC, and the PC is able to display the angle values at real time through the direct kinematics.

Thus, these steps can be systems that can make the least error rate of the shoe's size between the real one's size and the one displayed on the screen by the programmed global coordinate. In this study, as the 5-axis robot arm and the rotation plates move along the shoe's outsole, the shoe's outsole be shown on the screen by its own shape through the program. In addition, using the displayed screen and data's let us accurately control the paths of the shoe's buffing robot and bonding robot [1]. This study is consisted of the follows. In section 2, we show the whole system's configuration and explain how to extract the shoe's shape by the program in the system. In section 3, we descript how to use the base kinematics before the program. In section 4, we figure out the shoe's shape extraction program that obtains the robot arm's

location by transforming the encoders' value, which is applied to the robot arms. In section 5 and 6, we show the experiment result of this study.

2. SYSTEM CONFIGURATION

We display the shoe's outsole boding part shape by using the 5-axis, and create the auto-bonding robot's moving coordinate by the normal vector. There is the whole system configuration in figure 1.



Fig.1 System configuration.

The shoe's outsole is marked by 5-axis robot's probe, and the encoders' pulse values are read and counted in the PCL-833 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 C-program. At PCL-833, we can count in 24bit with 3-axis encoder counter card [2]. This is the brief explanation of the whole system configuration. The further information will be explained in the below.

We used E40H and E40S encoders of Autonics. Those incremental rotary encoders create 3 signals – A state, B state, Z state -, and these signals produce signals of the forward rotation and the reverse rotation. There could be around 50 points during the probe's marking. With those points, we can create spline lines and draw the shoe's outsole. Also, these

points help to obtain the normal vector. With 3 points, two vectors are subtracted and the perpendicular normal vectors are obtained by the vectors' outer product.

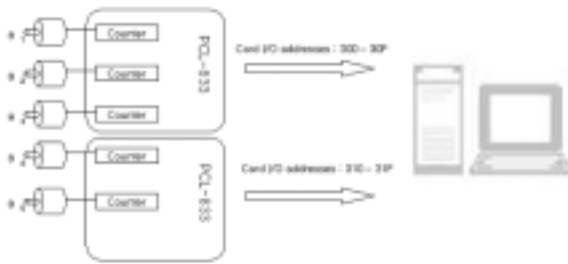


Fig.2 System Interface.

In figure 2, there is the way in which the two PCL-833 boards count the 5 encoders' pulses and transmit those values to 300-30F and 310-31F(the hexa address) in PC. Changing the address is enabled by adjusting the PCL-833 switch.

3. DENAVIT-HARTENBERG'S (D-H) DIRECT KINEMATICS

In this chapter, we show a determinant to calculate the global coordinates (x, y, z) after extracting θ value from robot. The determinant is obtained with kinematics equation and Denavit-Hartenberg variable representation. To lead the kinematics equation, we have to set up the standard coordinates first. The many links and the more complicated structure cause the difficult kinematics problem to solve in the geometrical way. Thus, we can solve the robot's kinematics problems efficiently and systematically by Denavit-Hartenberg's representation[3] [4].

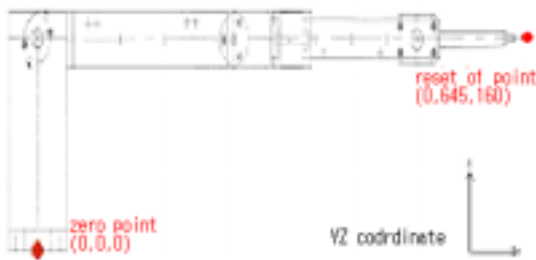


Fig.3 The calculated robot arm's form by the direct Kinematics.

From the robot shown in figure 3, the Denavit-Hartenberg variables extracted from the set-up coordinate are arranged and shown in the below Table1.

Table1. Denavit-Hartenberg's Variable of each axis.

Link	a_i	α_i	d_i	θ_i
1	0	90	d_1	θ_1^*
2	a_2	0	0	θ_2^*
3	a_3	0	0	θ_3^*
4	0	90	d_4	θ_4^*
5	a_5	0	0	θ_5^*

To solve all kinematics, we can work on by setting up a coordinate at each link as one pleases. But to effectively solve kinematics, it is useful to set up a coordinate well organized.

The most frequently used way is Denavit-hartenberg (D-H) representation. We can obtain the global coordinates by transforming pulse numbers to θ values and calculating [5]. The below determinant is 5-axis robot's calculation in the direct kinematics.

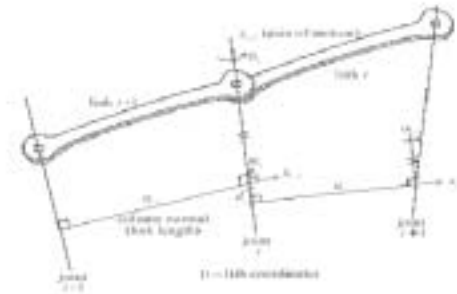


Fig.4 Set-up of Denavit-Hartenberg Coordinates.

Figure 4 shows links coordinates set-up and parameters set-up by D-H notation. And the geometric link parameters are as follows:

- θ_i (joint angle) : rotate about z_{i-1} from x_{i-1} to x_i
- d_i (distance) : translate along z_{i-1} from the origin of (i-1)th coordinates to x_i
- α_i (offset angle) : rotate about x_i from z_{i-1} to z_i
- a_i (common length) : translate along x_i from z_{i-1} to the origin of i th coordinates

Each link matrix is obtain with inputting the variables in Table 1 to the below determinant.

$$A_0^5 = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \tag{1}$$

The obtained 4x4 homogenous transformation matrixes are shown the below, which indicates relative location and direction of set-up coordinates $\{i\}$ and $\{i+1\}$.

$$A_1 = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$A_2 = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_2 & -s_2 & 0 & a_2 c_2 \\ s_2 & c_2 & 0 & a_2 s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$A_3 = \begin{bmatrix} c_3 & -s_3 & 0 & 0 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_3 & 0 & -s_3 & 0 \\ s_3 & 0 & c_3 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$A_4 = \begin{bmatrix} c_4 & -s_4 & 0 & 0 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_4 & 0 & s_4 & 0 \\ s_4 & 0 & -c_4 & 0 \\ 0 & 1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$A_5 = \begin{bmatrix} c_5 & -s_5 & 0 & 0 \\ s_5 & c_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_5 & -s_5 & 0 & a_5 c_5 \\ s_5 & c_5 & 0 & a_5 s_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Finally the homogenous transformation matrixes is as follows:
Where,

$${}^0_5A = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

$$r_{11} = c_5 (c_1 c_{23} c_4 - s_1 s_4) - c_1 s_{23} s_5 \quad (8)$$

$$r_{12} = -s_5 (c_1 c_{23} c_4 - s_1 s_4) - c_1 s_{23} c_5 \quad (9)$$

$$r_{13} = c_1 c_{23} s_4 + s_1 c_4 \quad (10)$$

$$r_{21} = c_5 (s_1 c_{23} c_4 + c_1 s_4) - s_1 s_{23} s_5 \quad (11)$$

$$r_{22} = -s_5 (s_1 c_{23} c_4 + c_1 s_4) - s_1 s_{23} c_5 \quad (12)$$

$$r_{23} = s_1 c_{23} s_4 - c_1 c_4 \quad (13)$$

$$r_{31} = c_4 s_{23} c_5 + c_{23} s_5 \quad (14)$$

$$r_{32} = -c_4 s_{23} s_5 + c_{23} c_5 \quad (15)$$

$$r_{33} = s_{23} s_4 \quad (16)$$

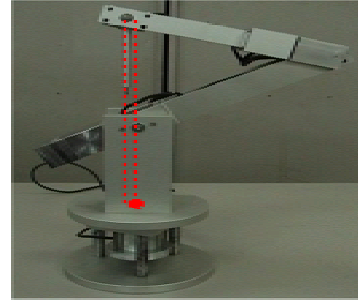
and

$$\begin{cases} p_x = a_5 a_{00} - c_1 s_{23} d_4 + c_1 c_2 a_2 \\ p_y = a_5 a_{10} - s_1 s_{23} d_4 + s_1 c_2 a_2 \\ p_z = a_5 a_{20} + c_{23} d_4 + a_2 s_2 + d_1 \end{cases} \quad (17)$$

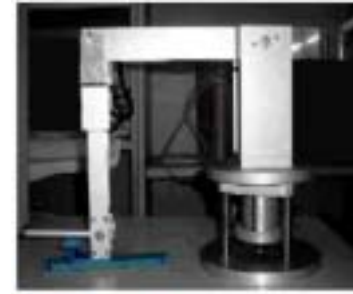
where ,

$$\begin{cases} a_{00} = c_5 (c_1 c_{23} c_4 - s_1 s_4) - c_1 s_{23} s_5 \\ a_{10} = c_5 (s_1 c_{23} c_4 + c_1 s_4) - s_1 s_{23} s_5 \\ a_{20} = c_4 s_{23} c_5 + c_{23} s_5 \end{cases} \quad (18)$$

In the upper determinant, the shoe's outsole points can be obtained by matrix multiplication between two coordinates at the origin point. In figure 3, as all encoders' values are reset, (O, 645, 160) is shown. That is, when the first axis moves, the rotation value is the value rotated away from the 645mm. In the figure 5(a), the red circle's location has to be the origin point. If the first axis is rotated, the rotated coordinate of the dot line's distance should be calculated.



(a)



(b)

Fig.5 5-axis robot arm's initial state.

However, when the first axis is rotated on the program, there can be high error rates because we calculated away from the 645mm if we did the robot arm's position like figure 5(a). In order to take care of this problem, we should compute the direct kinematics based on the way in figure 5(b). Then, after fixing the robot arm, we reset and reused.

4. THE EXTRACTION OF SHOE'S OUTSOLE COORDINATES

4.1 The initial screen of the shoe-outsole input program

In order to draw the outline of the shoe's outsole with *AutoCAD* or *CATIA*, a drawing of the shoe's outsole is necessary. 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. In this chapter, we cover how the auto-bonding robot finds the shoe-bonding paths based on the shape like the figure 5(b). We show the initial state of the shoe-outsole program after fixing the robot arm in figure 6[6][7].

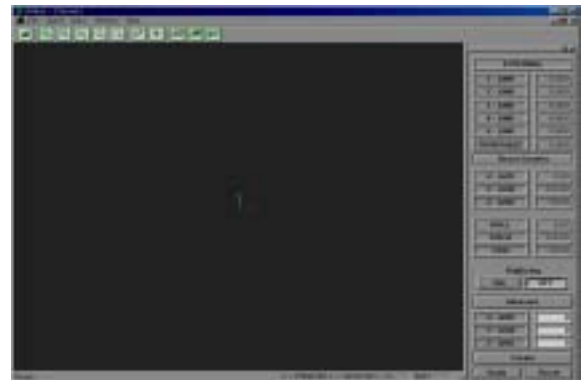


Fig.6 The initial screen of the shoe-outsole input program.

In this program, when the 5-axis robot marks a point, the point will be displayed on the screen. There are three axes in the center. As “MEASURE” button is pressed, the point of the 5-axis is displayed. “CREATE” button places a point on the screen by reading what a user enters the distance. There are more icons for multi-views like zoom-in and zoom-out.

4.2 The coordinate extraction program of the shoe’s

Outsole shape

In the chapter 4.2, there is a configuring process showing shoe’s outsole itself on the screen by the program as 5-axis robot rotates along fixed shoes’ outsole curve. In figure 7(a) and 8(a), there is a real shoe’s outsole model. In figure 7(b), 7(c) and figure 8(b),8(c), there are displays showing marking points of a shoe’s outsole based on the real shoe’s model.

In figure 7(b) and 8(b), there is the top view of the shoe’s outsole shape. That shoe outsole’s display is made of about 80 points by using the probes. We can see the shoe outsole’s shape by drawing the spline curves between points. To display this, the 5-axis robot narrowly marks points and a computer changes those points into the coordinates and displays those points on the screen. There are two outlines needed for the shoe outsole’s bonding part and the robot arm moves along between the two lines. We can obtain the normal vector with the figure like the above and overlapped 3 points at the top and bottom. In this study, it is subjected to obtaining the outline points of a shoe, the two outlines lined between the outline points, and the normal vector based on the points. These data are transformed into a .dxf file to be used as a data of the auto-bonding robot. In figure 7(C) and 8(c), there is the shoe outsole’s shape in the 3-dimension.



Fig.7(a) Real shoe’s outsole model.

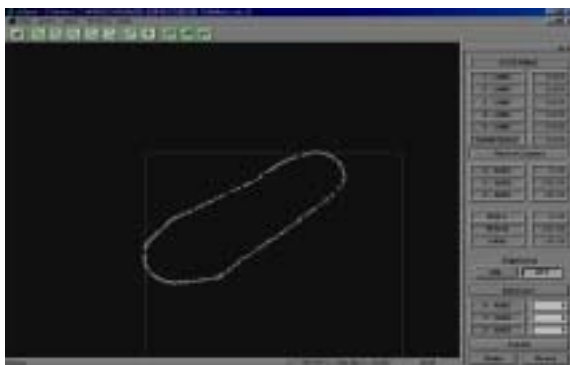


Fig.7(b) The top view of the shoe outsole’s shape.

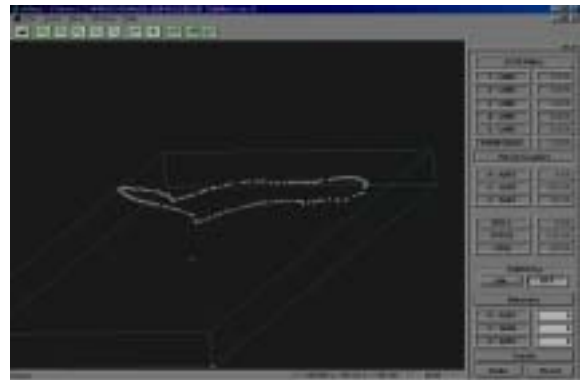


Fig.7(C) The shoe outsole’s shape in the 3-dimension.



Fig.8(a) Real shoe’s outsole model.

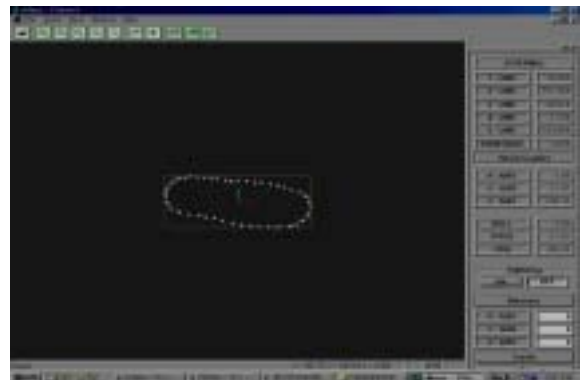


Fig.8(b) The top view of the shoe outsole’s shape.

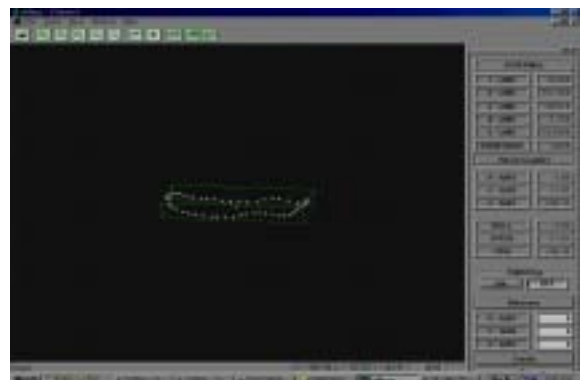


Fig.8(C) The shoe outsole’s shape in the 3-dimension.

5.RESULT AND DISSCUSION

The shoe's outsole as the 5-axis robot arm and the rotation plate's move along the shoe's outsole, the shoe's outsole be shown on the screen by its own shape through the program. In addition, using the displayed screen and data's let us accurately control the paths of the shoe's buffing robot and bonding robot. Figure 9 and figure 10, there is shoe's outsole shape in which there are spline lines connecting each point at *AutoCAD's* displayed window after transforming probe's marking points, a shoe's outsole points shown in figure 7(c) and figure 8(c) into a *.dxf* file [8].

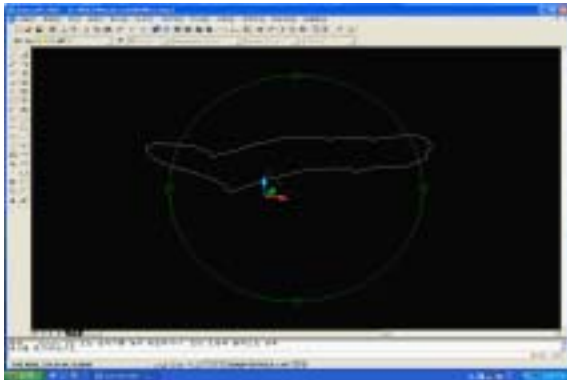


Fig.9 Shoe's outsole shape in CAD program.

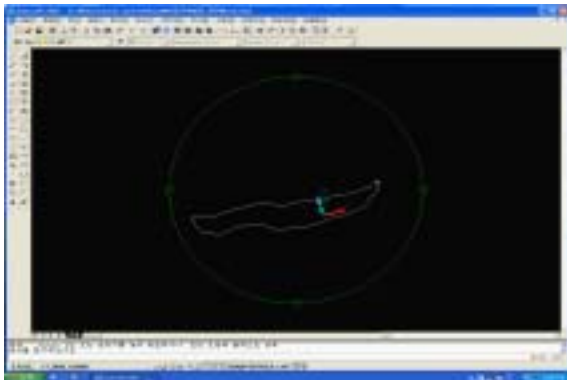


Fig.10 Shoe's outsole shape in CAD program.

6. CONCLUSIONS

The 5-axis robot should mark the shoe's outsole fixed on the rotation plate and display the shape of the shoe outsole while pointing the shoe moving on the plate. However, in order to have this job done, the distance between the 5-axis robot and the rotation plate is supposed to be fixed and the 5-axis and the rotation plate are supposed to be fixed to the same axis on the *xyz* coordinates as well. In the case of a shoe rotated on the rotation plate, the encoders read the rotated angle and the rotation plate moves that much. Then the robot arm points. That means the mathematical formula is needed between the 5-axis robot and the rotation plate.

In this study, we suggested how to fine the shoe's bonding path – the moving path of the auto-bonding robot. It is able to make the moving coordinates of the auto-bonding robot by obtaining the normal vector and displaying the shape of the shoe outsole bonding part with 5-axis robot. The 5-axis robot having an encoder at each joint for inputting a shape and the direct kinematics helped to obtain the coordinates of the last joint among 5 joints in the 5-axis robot arm. In order to do

this, the 5-axis robot's encoder pulse values transmit to the PCL-833 and through counting the values and computing the direct kinematics, it is able to display the shoe outsole's shape. While the robot arm is moving along the shoe's curve, the shape is displayed along the its curve on the screen through the program. It is also possible to control the buffing robot and the bonding robot of a shoe with the displayed screen and data. This study is one of processes in shoe FA (Factory Automation) and will help to reduce labor cost. With helping the deteriorated shoe FA, the productivity improvement will be expected as well.

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