Precise Position Control of Shoe-uppers for Screen Printing Machine Using SCARA Robot

Trong Hieu Bui [1], Anh Tuan Bui [2], Thanh Huy Phung [1]

[1] Faculty of Mechanical Engineering, HCMC University of Technology, HCMC, Vietnam
hieutkm@gmail.com, thanhhuy.phung@gmail.com
[2] Faculty Mechanical Engineering, Ly Tu Trong Technical College, HCMC, Vietnam
anhtuanbm88@gmail.com

Abstract. This paper proposes a new method to enhance precise position control of shoe-uppers for screen printing machine. The method is based on control of SCARA robot and image processing. The system has a SCARA robot attached a suction plate on its end effector, a fixed table and a conveyor system for screen printing machine. The suction plate takes supplied a shoe-upper on fixed table and calibrates its position from the table to conveyor. Position errors are eliminated during robot's motion. The SCARA robot is controlled by a simple PD controller. The effectiveness of the method is verified through a model-based simulation and its results.

Keywords: Inverse kinematics, Kinetics, SCARA robot, Image processing.

1 Introduction

Recently, various products of leather textile industry have decorations printed by screen printing machines. Especially in sport shoes, many types of printed decorations make shoes become more beautiful and valuable. In fig. 1, the parallel stripes are used as press-segments.

Fig. 1. Shoes with white stripes

These stripes are printed by automatic printing machines through many stages then dried up automatically with drying mechanism inside. These screen printing machines reduce stages and save time, labour, cost of products. However, shoe-uppers supplied for printing machine has been executed totally by hand. This work depends on the experience and psychology of workers, so it increases the errors, labour charge and price of products. This affects to next stage, which is sewing contour lines on printed stripes which could make more waste products. So, the problem is how to innovate the technology in order to optimize and automate the feeding stage for the conveyor of screen printing machines.

To solve this problem, some feeder systems for screen printing machines have recently been developed. Trong Hieu Bui et al. [6] developed successfully a ball screw feeder system. But this system is pretty bulky and not flexible. It's only suitable for screen printing machines with stations along line.

This research proposes another method that is able to apply many types of screen printing machines using SCARA robot. SCARA robot may be applied to enhance precision of shoe-uppers's position on the conveyor of screen printing machines. This can be achieved from SCARA robot's wide flexible operation range. SCARA will eliminate the position errors of shoe-uppers when it moves its joints. The objective of this project is to be applied in many fields outside leather and shoes industry as medical service or fuel supplying.

The executive steps to eliminate the errors of shoe-uppers by using SCARA robot are as follows

- *Step 1*. A shoe-upper is located on the fixed table.

- *Step 2*. To reduce noise, a CCD camera (put above fixed table) takes an image of current shoe-upper. Apply image processing to calculate the geometric properities of this image as centroid and oriented angle.

- *Step 3*. Use a SCARA robot moves the shoes upper from fixed table to conveyor of screen printing machine. The SCARA's end-effector moves to the center of the image, then moves to a desired position in the conveyor. The rotation error will be adjusted by end-effector after that.

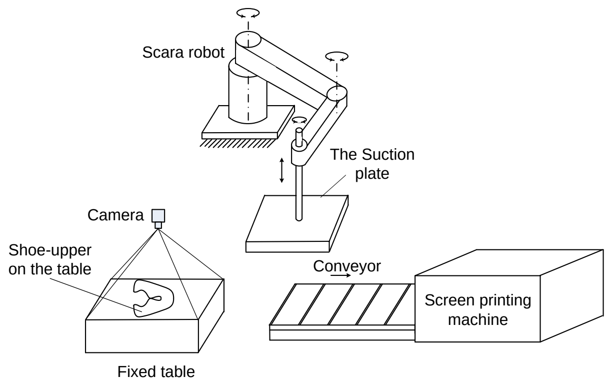


Fig. 2. The process of eliminating errors using a SCARA robot

2 System modelling

2.1 Systematic coordinators and notations

To analyse the system, the coordinate are set as fig. 3. (Oxy) is the global coordinate system, which has the origin O at the origin of the Scara robot; (Iuv), (Au_1v_1) and (Bu_2v_2) are the coordinate systems attached to the image, the table and the conveyor respectively. For the sake of simplicity, it is assumed that the captured image covers the fixed table. This could be achieved by camera calibration. The coordinates of local origins in the global system are

$I(x_I, y_I), A(x_A, y_A), B(x_B, y_B)$. The SCARA robot is described in 2D as **Fig. 3(b)**. ($O_1x_1y_1$) is local coordinate system, θ_1 and θ_2 are joints angles, L_1 and L_2 are lengths of the arms. In 2D global system, the coordinates of end-effector is (p_x, p_y).

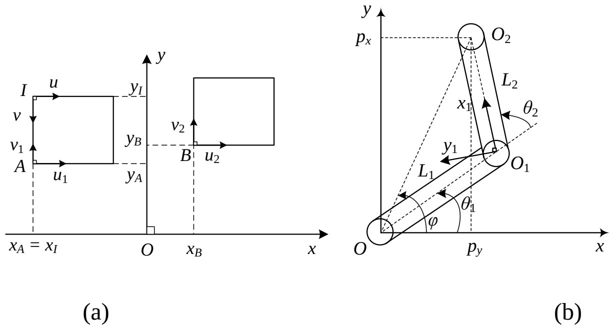


Fig. 3. The relationship of coordinate systems

Transformation from the image coordinate to the robot coordinate:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} 1/k_1 & 0 & x_I \\ 0 & -1/k_2 & y_I \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \quad (1)$$

Where k_1, k_2 are the scale factors by u and v directions respectively.

2.2 Shoe-uppers image processing

Similarly to paper [6], the centroid and oriented angle of shoe-uppers on image are used to control SCARA robot. The captured images are RGB image while the images used to calculate are binary image. Therefore, the images will be converted to binary image using Otsu's method after image pre-processing, then used to determine the geometric properties. It is also necessary to interest the reliable hardware and stability of light source.

Two geometric properties of area are concerned with the image are centroid of area $C(u_C, v_C)$ and oriented angle α. [4],[5],[6].

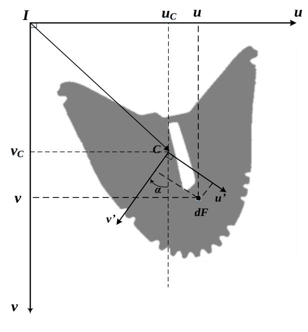


Fig. 4. The centroid and oriented angel of a shoe-upper in image coordinate (*Iuv*)

The centroid of plane area is

$$\begin{cases} u_C = \dfrac{1}{F}\sum_{u=1}^{n} F(u,v)\times u \\ v_C = \dfrac{1}{F}\sum_{v=1}^{m} F(u,v)\times v \end{cases} \tag{2}$$

Where *m* x *n* is size of image, $F(u,v)$ is the value at pixel (u,v), F is sum of all pixel values.

And the oriented angel α

$$\alpha = \frac{1}{2}\operatorname{atan}\left(\frac{-2\left(\sum_{1\le u\le n, 1\le v\le m} (u-u_C)(v-v_C)F(u,v)\right)}{\left(\sum_{1\le v\le m} (v-v_C)^2 F(u,v) - \sum_{1\le u\le n} (u-u_C)^2 F(u,v)\right)} \right) \tag{3}$$

2.3 Position of end effector

With a SCARA as fig. 3b, the position of end-effector in 2D:

$$\begin{bmatrix} p_x \\ p_y \end{bmatrix} = \begin{bmatrix} L_2\cos(\theta_1+\theta_2) + L_1\cos(\theta_1) \\ L_2\sin(\theta_1+\theta_2) + L_1\sin(\theta_1) \end{bmatrix} \tag{4}$$

Hence,

$$p_x{}^2 + p_y{}^2 = \left(L_2\cos(\theta_1+\theta_2) + L_1\cos(\theta_1)\right)^2 + \left(L_2\sin(\theta_1+\theta_2) + L_1\sin(\theta_1)\right)^2 \tag{5}$$

With configuration as fig. 3b:

$$\Rightarrow \theta_2 = \mathit{arccos}\left(\frac{p_x{}^2 + p_y{}^2 - L_1{}^2 - L_2{}^2}{2L_1L_2} \right) \tag{6}$$

$$\Rightarrow \theta_1 = \arctan\left(\frac{p_y}{p_x}\right) - \arccos\left(\frac{p_x^2 + p_y^2 + L_1^2 - L_2^2}{2L_1\sqrt{p_x^2 + p_y^2}} \right) \tag{7}$$

To take the shoe-upper, the end-effector should go to the calculated center of the shoe-upper image. From eq. (1):

$$\begin{cases} p_x = \dfrac{u_C}{k_1} + x_I \\ p_y = -\dfrac{v_C}{k_2} + y_I \end{cases} \tag{8}$$

After taking the shoe-upper, the robot move to get the desired position (p_{xd}, p_{yd}) on the conveyor. When the moving is accomplished, the end-effector rotate an angle Ω:

$$\Omega = \alpha - \alpha_d - \theta_1 - \theta_2 \qquad (9)$$

Where α_d is desired oriented angle of the reference shoe-upper on the conveyor.

2.4 Dynamics of SCARA robot

Dynamic equations of SCARA robot is determined using Lagrangian method. Firstly, only two joints (θ_1, θ_2) change to take and move the shoe-upper, after that, the end-effector rotates independently, so it is able to consider the robot as a two link robot. Consider this model of SCARA robot contains 2 rods with masses *M1, M2* and length of rods are *L1, L2*. The mass of motor attached on the first link is *M3* and the motor and end-effector on second link is *M4* as fig. 5.

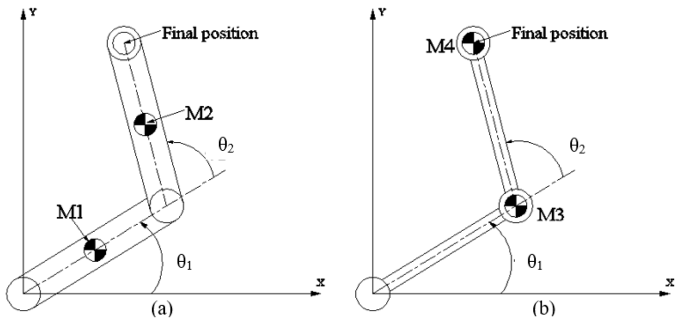


Fig. 5. The parts of SCARA robot

TP1: consider 2 links as 2 homogeneous rods with masses *M1, M2* and length *L1, L2.*

TP2: 2 links are considered 2 point masses *M3, M4* attached on 2 rods without mass and have length *L1*, *L2*.

Lagrangian function [2]:

$$L = K - P \qquad (10)$$

Where *L*: Lagrangian, *K*: The kinetic energy of body, *P*: The potential energy of body.

Lagrangian equation describes the dynamics of a link robot

$$\tau_i = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} \qquad (11)$$

Where τ_i is torque exerted on each joint, $i = 1, 2$.

While two joints moving, assume potential energy equals zero *(P = 0; L = K).*

The kinetic energy of each mass of SCARA robot [2]:

$$K_i = \frac{1}{2} M_i v_{Ci}^T v_{Ci} + \frac{1}{2}\, {}^i\omega_i^T \, {}^{Ci}I_i \, {}^i\omega_i, \qquad\qquad i = 1..4 \tag{12}$$

Where v_{Ci} : the linear velocity at the center of mass *i*.

${}^{Ci}I_i$: The inertia tensor with respect to center of mass *i*.

ω_i : the angular velocity of the mass *i*.

The model of SCARA robot could be divided into 2 separated parts

System TP1 with 2 homogeneous rods with masses M1, M2:

$$\begin{cases} \tau_{11} = \ddot{\theta}_1 \left[M_2 L_1^2 + \frac{1}{3} M_2 L_2^2 + M_2 L_1 L_2 c_2 + \frac{1}{3} M_1 L_1^2 \right] \\ -\dot{\theta}_1 \dot{\theta}_2 M_2 L_1 L_2 s_2 + \ddot{\theta}_2 \left(\frac{1}{3} M_2 L_2^2 + \frac{1}{2} M_2 L_1 L_2 c_2 \right) - \frac{1}{2} \dot{\theta}_2^2 M_2 L_1 L_2 s_2 \\ \tau_{21} = \ddot{\theta}_2 \left(\frac{1}{3} M_2 L_2^2 \right) + \ddot{\theta}_1 \left(\frac{1}{3} M_2 L_2^2 + \frac{1}{2} M_2 L_1 L_2 c_2 \right) + \frac{1}{2} \dot{\theta}_1^2 M_2 L_1 L_2 s_2 \end{cases} \tag{13}$$

System TP2 contains 2 point masses M3, M4:

$$\begin{cases} \tau_{12} = \ddot{\theta}_1 \left[M_3 L_1^2 + M_4 L_1^2 + 2 M_4 L_1 L_2 c_2 + M_4 L_2^2 \right] - 2 \dot{\theta}_1 \dot{\theta}_2 M_4 L_1 L_2 s_2 \\ \quad + \ddot{\theta}_2 \left(M_4 L_2^2 + M_4 L_1 L_2 c_2 \right) - \dot{\theta}_2^2 M_4 L_1 L_2 s_2 \\ \quad \tau_{22} = \ddot{\theta}_1 \left(M_4 L_2^2 + M_4 L_1 L_2 c_2 \right) + \ddot{\theta}_2 \left(M_4 L_2^2 \right) + \dot{\theta}_1^2 M_4 L_1 L_2 s_2 \end{cases} \tag{14}$$

The dynamic equations of SCARA robot

$$\begin{cases} \tau_1 = \tau_{11} + \tau_{12} \\ \tau_2 = \tau_{21} + \tau_{22} \end{cases} \tag{15}$$

3 Control process

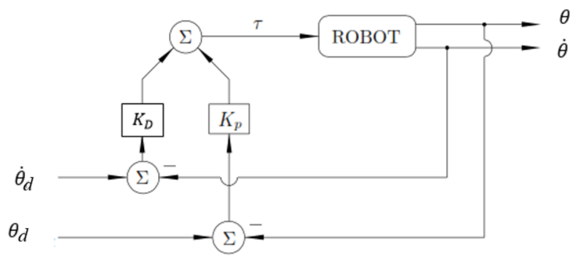


Fig. 6. Scheme of SCARA robot control

Consider the SCARA robot with dynamic equation given by [1] as follows:

$$M\left(\theta\right)\ddot{\theta}+V\left(\theta,\dot{\theta}\right)=\tau \tag{16}$$

Where $\theta=[\theta_1,\theta_2]^T$

And the following PD control law is given as shown in **Fig. 7**:

$$\tau=K_P E+K_D\dot{E} \tag{17}$$

where $E=\theta_d-\theta$; K_P, K_D are diagonal gain matrices and positive definite.

Using Lyapunov's method to proof the globally asymptotically stability of robot. A candidate Lyapunov function is chosen as [1]:

$$v=\frac{1}{2}\dot{\theta}^T M\left(\theta\right)\dot{\theta}+\frac{1}{2}E^T K_P E \tag{18}$$

The first derivative of Eq. (17) with respect to time is obtained as follows:

$$\begin{aligned}\dot{v}&=\dot{\theta}^T M\left(\theta\right)\ddot{\theta}+\frac{1}{2}\dot{\theta}^T\dot{M}\left(\theta\right)\dot{\theta}-\dot{\theta}^T K_p E\\&=\dot{\theta}^T M\left(\theta\right)\ddot{\theta}+\frac{1}{2}\dot{\theta}^T\dot{M}\left(\theta\right)\dot{\theta}-\dot{\theta}^T\left[M\left(\theta\right)\ddot{\theta}+V\left(\theta,\dot{\theta}\right)+K_D\dot{\theta}\right]\end{aligned} \tag{19}$$

Hence

$$\dot{v}=\dot{\theta}^T\left[\frac{1}{2}\dot{M}\left(\theta\right)-V_m(\theta,\dot{\theta})\right]\dot{\theta}-\dot{\theta}^T K_D\dot{\theta} \tag{20}$$

where

$$\dot{\theta}^T\left[\frac{1}{2}\dot{M}\left(\theta\right)-V_m(\theta,\dot{\theta})\right]\dot{\theta}=0 \tag{21}$$

From Eq. (21), Eq. (22) leads to:

$$\dot{v}=-\dot{\theta}^T K_D\dot{\theta}=-\dot{\theta}_1^2 K_{D1}-\dot{\theta}_2^2 K_{D2}<0\left(\forall\theta\right) \tag{22}$$

According to Lyapunov's method from Eqs. (19), Eq. (18) and (23), the system is globally stability.
The nonlinear differential equations of system are:

$$\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix}=M\left(\theta\right)^{-1}\begin{bmatrix}K_{P1}\left(\theta_{1d}-\theta_1\right)-K_{D1}\dot{\theta}_1\\ K_{P2}\left(\theta_{2d}-\theta_2\right)-K_{D2}\dot{\theta}_2\end{bmatrix}-V\left(\theta,\ddot{\theta}\right) \tag{23}$$

$$\begin{cases}\tau_1=K_{P1}\left(\theta_{1d}-\theta_1\right)-K_{D1}\dot{\theta}_1\\ \tau_2=K_{P2}\left(\theta_{2d}-\theta_2\right)-K_{D2}\dot{\theta}_2\end{cases} \tag{24}$$

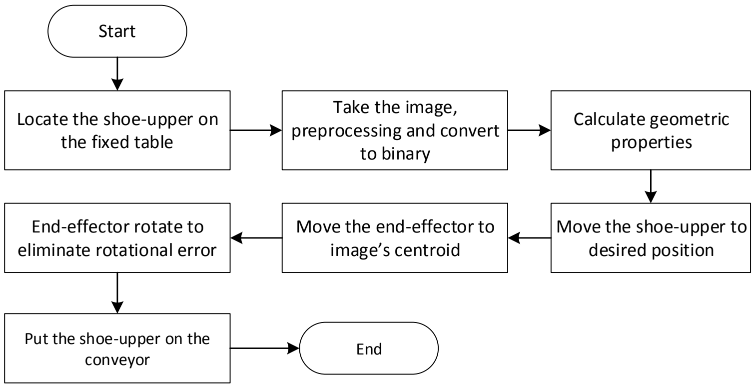


Fig. 7. Algorithm scheme of eliminating errors

4 Simulation and results

The robot parameters: L1= L2 = 0.5 m; M1 = M2 = M3 = M4 = 1kg.

Images used to simulate: (1115 x 912) pixels.

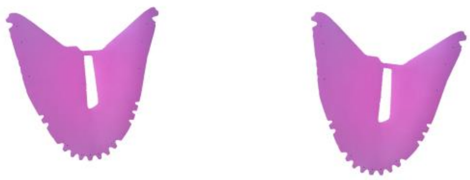
Systematic parameters: $x_A = x_I = -650$ mm; $y_A = 500$ mm; $x_B = 650$ mm; $y_B = 500$ mm; $k_1 = 7.5$; $k_2 = 6.5$

Desired centroid and oriented angle of the reference shoes upper on the conveyor in global frame: $x_{Cr} = 720.7325$ mm; $y_{Cr} = 572.0748$mm; $\alpha_{Cr} = 32.9706$ (degrees)

$Kp_1 = 20$; $Kd_1 = 10$; $Kp_2 = 15$; $Kd_2 = 10$.

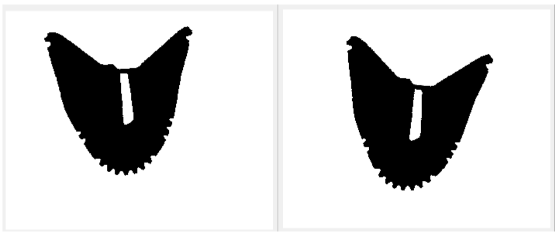
Fig 8a. shows the image used in simulation process. Firstly, the image of supplied shoe-upper is converted into binary image as fig. 9a and the geometrical properties are determined in the coordinate system attached to the image using eqs. (2) and (3). Suppose that in beginning, the shoe-upper is located in the table having parameters as above. Our objective is to make the supplied image have the same geometrical properties with the reference in the conveyor after transformations that simulate motions of the system.

The result image after simulation is shown in binary in fig 9b.



(a) (b)

Fig. 8. Supplied image (a) and desired image (b) of shoe-upper



(a) (b)

Fig. 9. Binary image of supplied shoe-upper's image before (a) and after simulation (b)

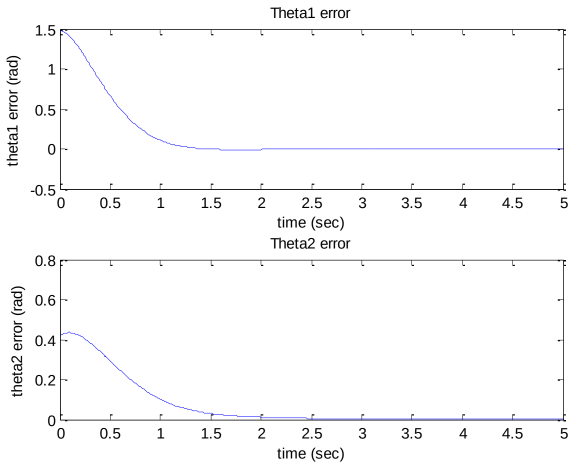


Fig. 10. Joints when end-effector move from original position to supplied image's centroid

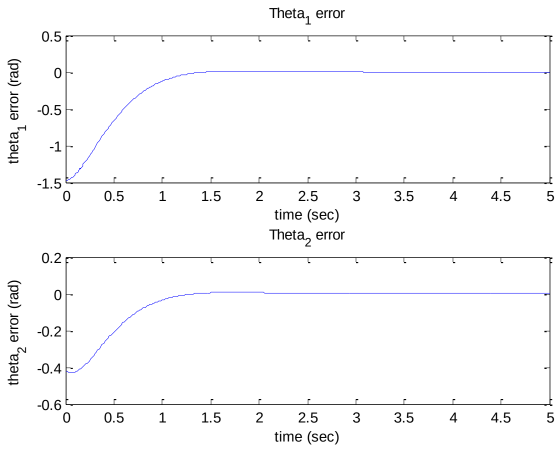


Fig. 11. Joints when end-effector move from supplied image's centroid to desired position

Fig. 10 shows errors of joints angles from the initial position to the calculated position in the process to take the shoe-upper located in the table whilst fig. 11 shows errors of joints angles in next step, which is move from the reached position to the reference position in the conveyor.

5 Conclusions

This paper introduced a precise position control of shoe-upper using image processing techniques and SCARA robot for the screen printing machine which is used to print the stripes on the shoe-upper. This research obtains as analyse the inverse kinematic model of SCARA robot to control precise position of shoes-upper. And analyse the kinetic model of SCARA robot to simulate the motion of end effector from the conveyor to the fixed table and return. The stability of the controller is proven through simulation results.

6 References

[1] John J. Craig, *Introduction to Robotics*, Prentice Hall, 2005.

[2] Phillip John McKerrow, *Introduction to Robotics (Electronic Systems Engineering Series)*, Addison-Wesley Pub. Co., 1991.

[3] Saeed B. Niku, *Introduction to Robotics: Analysis, Systems, Applications*, Prentice Hall, July 2001.

[4] Dietmar Gross, Werner Hauger, Jörg Schröder, Wolfgang A. Wall, Nimal Rajapakse, *Engineering mechanics 1 (Statics)*, Springer, 2009.

[5] Wilhelm Burger and Mark J. Burge, *Principles of Digital Image Processing Core Algorithms*, Springer - Verlag London Limited, 2009.

[6] Trong Hieu Bui and Thanh Huy Phung, "Design and Fabrication of Precise Shoe-upper Feeder System for Screen Printing Machine in Shoe Industry", *Proceedings of the International Conference on Engineering Mechanics and Automation*-ICEMA3 (2014), pp.213-220.