Multi-Robotic Arms Automated Production Line

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***Abstract*—In response to the booming industrial automation, three commonly used industrial robots including one parallel type robot, one gantry type robot, and two six-axis serial robots will be self-developed in this study. The six-axis robot arm can be controlled by using Kinematics method. Furthermore, a fifth-order-polynomials method is used to limit accelerations and velocity on each joint to achieve continuity. Arc path of the robotic arm can be achieved by the three-points-arc interpolation. Therefore, trajectories for gluing path planning will be successfully generated. Moreover, vision devices are used to inspect the work pieces after the laser engraving. In addition, the storage system provides storage of unassembled and finished workpieces. Finally, the system integration of all equipment will be completed to achieve a customized multifunction gluing and assembly line by self-developed robotic arms.**

Keywords-automation; robotic arm; interpolation; forward and inverse kinematics

I. INTRODUCTION

Nowadays, products needed to be inspection or different arranged will always requires a lot of manpower. Therefore, more and more specific automation equipment is earnestly to be needed. A robotic arm has similar functions of a human arm, so that can be instead of workers in high-risk environments and highly repetitive work items. The basic types of robotic arms can be divided into parallel, gantry Cartesian robot, and serial robotic arm

Parallel manipulators are often used in industries that require high precision and rapid movement [1]-[2]. Due to the control simple, high precision and rigidity properties, the gantry robot arm are often used in various types of processing machines [3]-[4]. Serial manipulators are also widely used in automobile manufacturers, automotive components and electronics related industries [5-6].

Robotic arm is suitable used in repetitive and dangerous work environments, therefore in today's automated production line plays an important role. In this study, robot arm design, assembly, maintenance, electronic control systems, electromechanical integration, production line planning, will be on campus to show the ability of the entire line of output. It will facilitate the practical skills upgrading and industry cooperation willing increasing.

II. AUTOMATION PRODUCTION LINE

Robotic arms are the main operators in the automation production line. The overall system, including parallel, gantry type and six-axis vertical robots controlled by a program logic controller (PLC), is shown in Fig. 1.

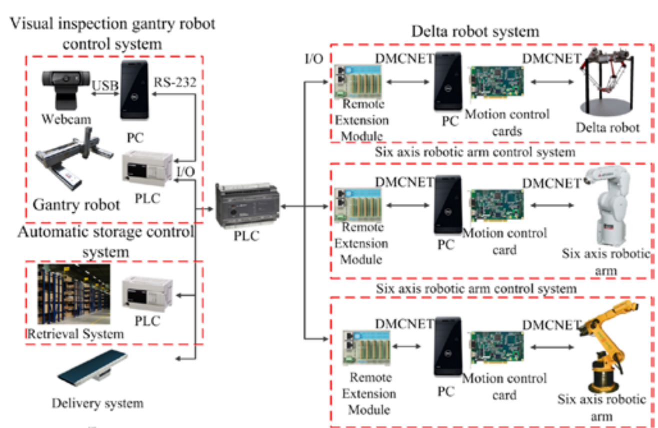


Figure 1. System architecture.

The automation line shown in Fig.2 composed of station I, II, II, and IV. An auto-loading apparatus is setup at the starting place in Station I to provide processing piece continuously, and whether the processing piece is detected by a photoelectric sensor. It will be pushed to the specific area when processing piece is detected, then engraved on the user defined pattern by using the laser module mounted in the delta robot. When the above works finished, the processing piece will be transported to Station II by using the Conveyor I. Station II is mainly composed of a Gantry-type robotic arm and a PC-based vision inspection system to carry out the quality management of the processed piece. Unqualified items will be directly passed to the waste area by the Conveyor Ⅰ. When the piece is inspected qualified, it will be moved to conveyor II and sent to Station III.

There are two 6-axis robotic arms and a gluing device in Sestion III. First, the piece form Station II is moved to standby area by 6-axis robotic arm I, and then the workpiece will be griped by 6-axis robotic arm II to do the gluing operation. When finish gluing process, 6-axis robotic arm II will move it back to standby area. Next, 6-axis robotic arm I will go to take the cover from storage system and the work piece in standby area combination. Finally, the finished work piece will be sent by 6-axis robotic arm I to stotage system in Station IV.

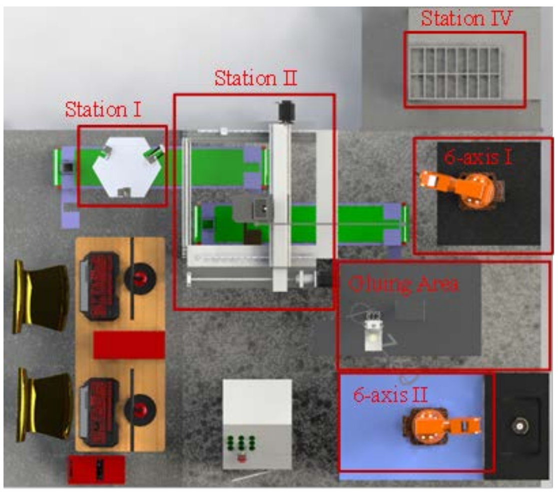


Figure 2. Automation production line configuration.

III. 6-AXIS ROBOTIC ARM

The main topic is to repair and establish a robot controller for 6-axis robotic arm I. Six-axis robotic arm is automatic control equipment that mimics human arm action and performs a wide range of tasks. It is suitable used in repetitive and dangerous work environments. Due to the general robotic arm factory cannot provide the service for more than a decade of mechanical arm related maintenance and software update. In this study, we will repair related hardware and develop the robot control system to make the 6-axsi robotic arm normal operation. First, motors will be replaced according to the wattage, rated speed, rated torque and rated current of the old motors in the original 6-axis robotic arm. Because the new motor flange is different from the previous motor, the motor adapter plate was processed to make new motors can be fixed to the 6-axis robot arm.

In the robot control system, servo motors and remote IO will be adopted and controller by a motion control card in a PC. The servo motors are controlled by the motion control card according to the control program, so that the 6-axis robotic arm can complete the action and trajectory movement. Then gripper is acted by remote IO module to finish pick and place function.

3-1 Kinematics

Kinematics is mainly used to analyze the robotic mechanical arm movement conditions in space. Through the relative positions and angles of each joint and link in three-dimensional space, the relationships including time, displacement, speed and other variables, among each axis of the complete robot arm and the connecting link are constructed. Robot kinematics can be divided into forward kinematics and inverse kinematics. Forward kinematics can be used to find the position and attitude of the manipulator in three-dimensional space the by using the known rotation angles and parameters of each axis. Inverse kinematics can be used to obtained the turning angle of each axis join according the information of the attitude and position of a robotic arm in the three-dimensional space.

A. Forward Kinematics

Denavit-Hartenberg (D-H) method that uses four parameters is the most common method for describing the robot kinematics. it is composed of serial links which are affixed to each other revolute or prismatic joints from the base frame through the end-effector. The position and orientation of the end-effector can be calculated in terms of the joint variables according D-H method. There are four parameters a (link length), α (link angle) , d (link offset) and θ (joint angle). The related D-H parameters and coordinate system are described in the 6-axis robot arm represented as Fig. 3. The corresponding link parameters are listed in Table 1, and D-H transformer matrices can be obtained as (1) [7]-[8].

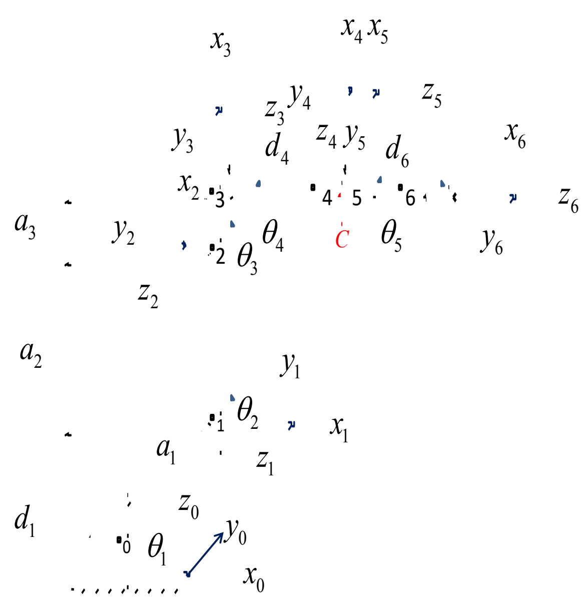


Figure 3. Schematic diagram of the 6-axis robot arm.

TABLE I. D-H PARAMETERS

JOINT	θ	d	α	a
J_1	θ_1	d_1	90°	a_1
J_2	θ_2	0	0°	a_2
J_3	θ_3	d_3	90°	0
J_4	θ_4	d_4	-90°	0
J_5	θ_5	0	90°	0
J_6	θ_6	d_6	0°	0

$$
\begin{aligned}
{}^{i-1}_{i}T &= Rot(x,\alpha_{i-1})Trans(a_{i-1},0,0)Rot(z,\theta_i)Trans(0,0,d) \\
&= \begin{bmatrix} c\theta_{i-1} & -s\theta_{i-1}c\alpha_i & s\theta_{i-1}s\alpha_i & a_{i-1}C\theta_{i-1} \\ s\theta_{i-1} & c\theta_{i-1}c\alpha_i & -c\theta_{i-1}s\alpha_i & a_{i-1}S\theta_{i-1} \\ 0 & s\alpha_i & c\alpha_i & d_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{aligned} \tag{1}
$$

According (1), the transformer matrix of each joint can be represented as (2)-(7), in which C_i denotes $Cos\theta_i$; S_i denotes $Sin\theta_i$; S_{ij} denotes $Sin(\theta_i+\theta_j)$; C_{ij} denotes $Cos(\theta_i+\theta_j)$.

$$
A_1 = \begin{pmatrix} c_1 & 0 & s_1 & c_1 a_1 \\ s_1 & 0 & -c_1 & s_1 a_1 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \ (2) \quad A_2 = \begin{pmatrix} c_2 & -s_2 & 0 & c_2 a_2 \\ s_2 & c_2 & 0 & s_2 a_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \ (3)
$$

$$
A_3 = \begin{pmatrix} c_3 & 0 & s_3 & 0 \\ s_3 & 0 & -c_3 & 0 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \ (4) \quad A_4 = \begin{pmatrix} c_4 & 0 & -s_4 & 0 \\ s_4 & 0 & c_4 & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{pmatrix} \ (5)
$$

$$
A_5 = \begin{pmatrix} c_5 & 0 & s_5 & 0 \\ s_5 & 0 & -c_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \ (6) \quad A_6 = \begin{pmatrix} c_6 & -s_6 & 0 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{pmatrix} \ (7)
$$

It is straightforward to calculate each of the link transformation matrices as follows:

$$
{}^{0}_{6}T = A = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6 = \begin{bmatrix} u_x & v_x & w_x & p_x \\ u_y & v_y & w_y & p_y \\ u_z & v_z & w_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}
$$

where $\boldsymbol{u} = [u_x \ \ v_y \ \ w_z]^T$, $\boldsymbol{v} = [v_x \ \ v_y \ \ v_z]^T$, $\boldsymbol{w} = [w_x \ \ w_y \ \ w_z]^T$, and $\boldsymbol{p} = [p_x \ \ p_y \ \ p_z]^T$ are the target position of the end effector, ***u***, ***v***, ***w*** and ***p*** are refer to attitudes and position, respectively.

B. Inverse Kinematics

Inverse kinematics refers to the use of the kinematics equations of a robot to determine the joint angle. The rotation angle of each joint, θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, can be obtained as follows by the known end-point of the tool is relative to the base coordinates, ${}^{0}P = \begin{bmatrix} end_x & end_y & end_z \end{bmatrix}^T$ and the direction vector ***u***, ***v***, ***w*** [9]. It can be seen from Fig. 5 that three axes of rotation joint 4, joint 5 and joint 6 of this robot's wrist intersect at a single point. Assume the point C in Fig. 3, which can be related to the origin as follow equation.

$$
C^0 = \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} = \begin{bmatrix} end_x \\ end_y \\ end_z \end{bmatrix} - toolx \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - tooly \begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} - toolz \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} - d_6 \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} \tag{9}
$$

The point C is in the positive direction of the $x_3 - y_3 - z_3$ coordinate axis and the point C related base coordinate can be reformulated as (10)

$$
\begin{bmatrix} C_x & C_y & C_z \end{bmatrix} = A_1 \times A_2 \times A_3 \times \begin{bmatrix} 0 & 0 & d_4 & 1 \end{bmatrix}^T \tag{10}
$$

Eq. (11) can be obtained as follows by solving (10).

$$
\begin{bmatrix} -a_1 + c_1 + C_y s_1 \\ C_z - d_1 \\ C_x s_1 - C_y c_1 \\ 1 \end{bmatrix} = \begin{bmatrix} a_2 c_2 + d_4(s_2 + s_3) \\ a_2 s_1 - d_4(c_2 + c_3) \\ d_3 \\ 1 \end{bmatrix} \tag{11}
$$

Then, θ_1 and θ_3 can be calculated from (11) and represented as (12) and (13), respectively.

$$
\theta_1 = \arctan\left(\frac{C_y}{C_x}\right) + \arcsin\left(\frac{d_3}{\sqrt{C_x^2 + C_y^2}}\right) \tag{12}
$$

$$
\theta_3 = \left(\arcsin\left[\frac{a_1^2 + C_x^2 + C_y^2 - 2a_1(C_x c_1 + C_y s_1) + (C_z - d_1)^2 - a_2^2 - d_3^2 - d_4^2}{2a_2 d_4}\right]\right)
$$

or

$$
\theta_3 = \left(\pi - \arcsin\left[\frac{a_1^2 + C_x^2 + C_y^2 - 2a_1(C_x c_1 + C_y s_1) + (C_z - d_1)^2 - a_2^2 - d_3^2 - d_4^2}{2a_2 d_4}\right]\right) \tag{13}
$$

Finally, θ_2, θ_5, θ_4, θ_6 can be solved in order as (14)-(17). Some solutions will be two and we decision the solution according to the actual location.

$$
\theta_2 = \left(\arctan\left[\frac{v_2 r_1 - v_1 r_2}{u_1 v_2 - u_2 v_1} / \frac{r_2 u_1 - u_2 r_1}{v_2 u_1 - v_1 u_2}\right]\right) \tag{14}
$$

$$\theta_5 = \arccos[S_{23}c_1 w_x + s_{23}s_1 w_y - c_{23}w_z]$$
or
$$\theta_5 = -\arccos\left[s_{23}c_1 w_x + s_{23}s_1 w_y - c_{23}w_z\right] \tag{15}$$

$$\theta_4 = \arctan\left[\frac{c_1c_{23}w_x + s_1c_{23}w_y + s_{23}w_z}{s_1w_x - c_1w_y}\right]$$
or
$$\theta_4 = \arctan\left[\frac{c_1c_{23}w_x + s_1c_{23}w_y + s_{23}w_z}{s_1w_x - c_1w_y}\right] + \pi \tag{16}$$

$$\theta_6 = \arctan\left[\frac{-(\mathrm{c}_1 s_{23}\,\mathrm{v}_x + s_1s_{23}v_y + c_{23}v_z)}{c_1s_{23}u_x + s_1s_{23}u_y + c_{23}u_z}\right]$$
or
$$\theta_6 = \arctan\left[\frac{-(\mathrm{c}_1 s_{23}\,\mathrm{v}_x + s_1s_{23}v_y + c_{23}v_z)}{c_1s_{23}u_x + s_1s_{23}u_y + c_{23}u_z}\right] + \pi \tag{17}$$

C. Path Planning

6-axis robotic arm path planning refers to the robot arm in space path of movement, which includes mechanical arm joints in motion displacement, velocity and acceleration. The general approach is to teach a few points on the moving path, and then the rotation of each axis joints will be analyzed by inverse kinematics. However, there is gap in each joint, making the arm kinematic point-to-point movement is not smooth movement or even showed irregular movement. Therefore, the robotic arm must be constrained to achieve the goal of restraining the joint speed and acceleration of each axis by interpolating each axis joint.

The joint position, velocity and acceleration of each axis can be represented by the fifth-order polynomial as (18) [10].

$$\begin{aligned}
\theta_{(t)} &= a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5 \\
\dot{\theta}_{(t)} &= a_1 + 2a_2t + 3a_3t^2 + 4a_4t^3 + 5a_5t^4 \\
\ddot{\theta}_{(t)} &= 2a_2 + 6a_3t + 12a_4t^2 + 20a_5t^3
\end{aligned} \tag{18}$$

The restrictions on speed and acceleration at the start point and the target point can be expressed as follows.

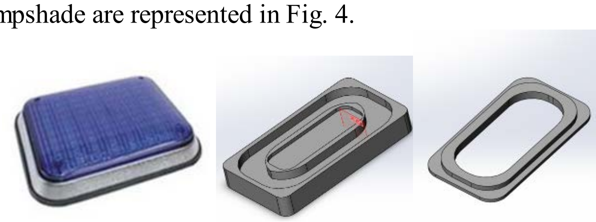
$$\begin{aligned}
\theta_0 &= a_0 \\
\theta_f &= a_0 + a_1t_f + a_2t_f^2 + a_3t_f^3 + a_4t_f^4 + a_5t_f^5 \\
\dot{\theta}_0 &= a_1 \\
\dot{\theta}_f &= a_1 + 2a_2t_f + 3a_3t_f^2 + 4a_4t_f^3 + 5a_5t_f^4 \\
\ddot{\theta}_0 &= 2a_2 \\
\ddot{\theta}_f &= 2a_2 + 6a_3t_f + 12a_4t_f^2 + 20a_5t_f^3
\end{aligned} \tag{19}$$

The coefficients in polynomials can be obtained by solving the above equations and list as follows.

$$\begin{aligned}
a_0 &= \theta_0 \\
a_1 &= \dot{\theta}_0 \\
a_2 &= \frac{\ddot{\theta}_0}{2} \\
a_3 &= \frac{20\theta_f - 20\theta_0 - (8\dot{\theta}_f + 12\dot{\theta}_0)t_f - (3\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^3} \\
a_4 &= \frac{30\theta_f - 30\theta_0 + (14\dot{\theta}_f + 16\dot{\theta}_0)t_f + (3\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^4} \\
a_5 &= \frac{12\theta_f - 12\theta_0 - (6\dot{\theta}_f + 6\dot{\theta}_0)t_f - (\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^5}
\end{aligned} \tag{20}$$

IV. Experiment

In order to demonstrate the related functions of the automation production line, the square lamp assembly will be shown in the study. The square lamp, lamp housing, and lampshade are represented in Fig. 4.



(a) (b) (c)

Figure 4. Assemble object: (a) Square lamp; (b) Lamp housing; (c) Lampshade.

A. Gluing Path Planning

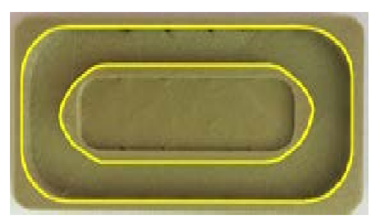


Figure 5. Glue path schematic.

Figure 6. Glue action.

The glue the path on the lamp housing is shown in yellow line in Fig. 5. From the yellow path we can see that the path contains four circular paths and four straight paths. Arc path of robot arm can be achieved using the three-points-arc interpolation by setting starting point, midpoint and end point. Fifth-order polynomial will be used to constrain the speed and acceleration in linear movement so that the end of the arm can perform linear motion. The actual gluing action can be seen in Fig. 6.

B. *Automation Production Line*

This study use the existing equipment such as visual inspection gantry, delta robot, two six axis robot arms are responsible for gluing and assembly operations. The whole production line can be divided into four stations, and actual automation production line is shown in Fig. 7. The process diagram is shown in Fig. 8 and the demo movie is list as follow link:

https://www.youtube.com/watch?v=jaAqhyZAxXE

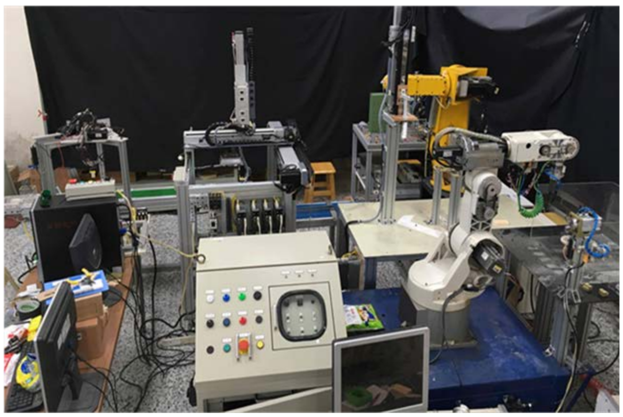


Figure 7. Automation production line.

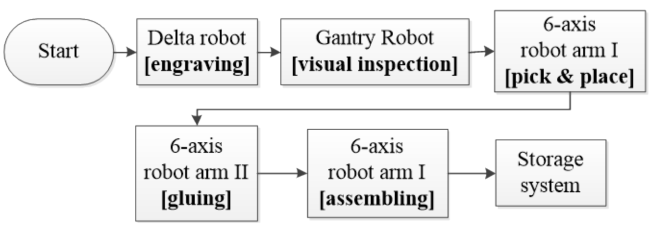


Figure 8. Process diagram.

V. CONCLUSION

An automated production line use of existing automation equipment and builds own six-axis arm for an automatic gluing line had been implemented in this study. The robot arm can be controlled by using Kinematics method. Furthermore, fifth-order-polynomials method is used to limit accelerations and velocity on each joint to achieve continuity. Arc path of robot arm can be achieved by the three-points-arc interpolation. Therefore, trajectories for gluing path planning will be successfully generated. In a section of the whole production line, the work piece can accomplish customized laser engraving and automatic defect inspection to increase effectiveness. The storage system provides storage of unassembled and finished work pieces. Finally, the system integration of all the devices and two six axis robotic arm have been finished to achieve customized multifunction gluing and assembly line

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REFERENCES

[1] D. Corinaldi, L. Carbonari, and M. Callegari, "Optimal motion planning for fast pointing tasks with spherical parallel manipulators", *IEEE Robotics and Automation Letters,* vol. 3, no. 2, pp. 735–741, 2018

[2] J. Zhao, F. Chu, and Z. Feng, "Kinematics of spatial parallel manipulators with tetrahedron coordinates", *IEEE Transactions on robotics,* vol. 30, no. 1, pp. 233–243, 2014.

[3] C. Chen, Y. Wu, C. Huang, and P. Hsueh, "The introduction of precision positioning and compensation technology in gantry-type platform", *2011 First International Conference on Robot, Vision and Signal Processing*, pp. 94–97, 2011.

[4] C. Zhang and Y. Chen, "Adaptive synchronization tracking control of dual-driving feed system for gantry-type machine tool", *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 2961–2966, 2017.

[5] J. Hatzis, P. Pelland, G. Hindman, "Implementation of a combination planar and spherical near-field antenna measurement system using an industrial 6-axis robot", *AMTA 2016 Proceedings*, pp. 1–6, 2016.

[6] B. Jan, F. Nils, I. Philipp, and T. Yukio, and C. Burkhard, "Comparative study of serial-parallel delta robots with full orientation capabilities", *IEEE Robotics and Automation Letters,* vol. 2, no. 2, pp. 920–926, 2017

[7] L. W. Tsai, *Robot Analysis*, Wiley-Interscience Publication, 1999.

[8] Mittal and Nagrath, *Robotics and Control* (1st ed) United States: McGraw-Hill Education, 2003.

[9] Y. S. Gong, M. G. Wu, Z. H. Zhong, X. H. Li, and W. Q. Chen, "Development of the Control Hardware IP for Kinematics/Inverse Kinematics", *Journal of the Mechatronic Industry*, pp. 61–76, 2013.

[10] Y. Guan, K. Yokoi, O. Stasse and A. Kheddar, , "On Robotic Trajectory Planning using Polynomial Interpolations", *IEEE International Conference on Robotics and Biomimetics*, pp. 111–116, 2005.