Development of Pick and Place Delta Robot

Chapter · March 2020

DOI: 10.1007/978-3-030-40271-6_47

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Abstract— This research aims to develop a prototype of 3-DOF robot that use for pick and place objects with high speed movement and low cost to produce, named parallel robot or delta robot. The robot can approach special applications with fast and smooth control. Thus, it is easy to movement in different positions. It is suitable for transporting workpieces or be able to move in various points. The payload can be up to 500 grams. In current application, it can be applied to the food manufacturing industry. Therefore, the robot prototype can be used for food industry companies or related industries field. The project has co-operative from both public sector and private sector. The research and development are conducted by the researchers from the public sector. The private sector provides support materials and equipment. After producing a prototype, the test is carried out by the private sector, evaluates the performance and satisfaction of users to use. When the prototype is completed, the private sector can be commercialized to market in the future.

Keywords— Delta robot, parallel robot, robot design, mechanical design

1 Introduction

Autonomous system in Thailand is required step forward to the future. Developer countries such as USA, Japan, and Germany have their own robot brand. These countries have many robot types to support in production line because labor cost is higher than industrial robots, and performance improvement is required.

Delta robot is a robot which aim to move very fast and accurate. Moreover, working space of delta robot is larger than SCARA robot. Designing delta robot is a new interested topic. However, teaching materials in schools do not support in real develop. Normally, teaching robotics in classroom is only teach in basic theory. Thus, this research created a prototype of delta robot that can use for replacing human labor.

Moreover, it can be used for studying in the basic theory of robotics, mathematical calculations, and programming design. The robot is designed for learning purpose and the structural robot can be used as knowledge to development of agricultural aid and understand for future designing.

For the food industry, they have processes which need to be packaged. The packaging process is necessary step because of not only the quality cleanliness of food products, but also the equally weight of the package. The packaging process has too many effects to the cost of production. Moreover, food industries also require speed. Focusing on the packaging process in Thai food industry, especially SMEs (Small and Medium Enterprises), the process still uses labors to do. Thus, the production is sometimes low efficiency from shortage labors. As issue from above, the research aims for benefits to use automatic robot technology and help to reduce such burden. Designing and constructing the high-speed robot for food packaging in Thailand have purpose to reduce importing robots from abroad. Moreover, the knowledge can be used for repair and improvement of the Delta robot. The high-speed picking up robot for food packaging, which the research team has designed or tested, uses equipment that available in Thailand market. It is flexible to install and enable users for adjusting job conditions easily.

Delta robots are parallel robots, which are consisted of many kinematic chains. There are many end effectors that can be changed. The important concept of delta robots is to use a parallelogram which is limited. There are movement of motion patterns in X, Y or Z direction without rotation only. The base of the robot is installed on top of the working area and stimulate all existing movements from the base of the three jointed arms in the middle. The ends of these arms are connected to the form of a small triangle. The triangle XYZ model can be operated with a linear actuator or direct control at the base. Therefore, Delta robots can move with high speed and high acceleration. At present, there are many delta robots in the world market. For example, Delta robot with 6 degrees of freedom developed by Fanuc, which included 3 degrees of rotation at the end-effector.

2 Related works

The concept design of Delta robot from many literatures have started from free body diagram creation [1][2][3][5], then find solutions of forward and inverse kinematics [4][6]. Finally, designing mechanism of delta robot has been implemented. Although the process of design in each related works are the same, the output results are different. Especially, The basic of mechanical design have the same idea [1][2][7][8], but the length of arms and some mechanism details have difference from purpose of usage such as food production, small workpieces, and cycle time. Thus, many researches have focused on improvement of Delta robot [7][9]. Not only speed and accuracy, but also controller and programing has been improved [9].

As mentioned from above, for education, the research might be too complex and difficult to study. Therefore, building Delta robot project based learning has been created for students and researcher who want to start study the Delta robot.

3 Principle of Delta Robot model

Principles of robot design is used to high speed handling for food packaging. Thus, parallel robot or delta robot has been selected. The design has been divided into 2 parts, mechanical part and electrical control. The mechanical part is designed with 3 legs. Each leg has a joint for control to the End Effector by order. There is an electric servo motor which drives each leg to move together. Each servo motor will move according to the position determined by Kinematics calculation at PLC control and transfer command via Modbus TCP/IP and CANOpen. The advantage of using delta robot is the robot can pick up faster than other robots such as SCARA robot and XY-table. It can be said that this delta robot is suitable for food production because of the speed of picking, weight, and installation area. It is also more advantageous than a normal robot. However, it has complex mathematical equations.

Designing delta robot has been separated to 4 main parts, Forward Kinematics, Inverse Kinematics, mechanical design, and Electrical design as follow:

3.1 Forward Kinematics (FK) Solution

The delta robot has 3-DOF of parallel robot. Each leg contains servo motor at the starting joint. The picture below has shown the dimension details of the parallel robot which is built.

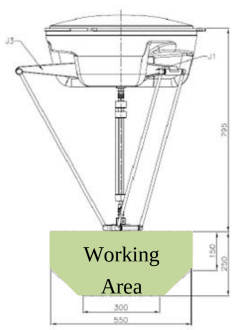


Fig. 1. The dimension and working area of delta robot

The 3-dof delta robot can control XYZ translation within its workspace. In this robot, the working area has been shown in figure 1. With the 3 legs which assigined as $i = 1,2,3$, each servo motor has been connected to the starting point which be called as B_i points (length L_B=145mm). The joint of the points are the hips. The B_i points have connected links L_1 with length 260 mm. the points at the end of L1 are the knees, have been called as A_i point. The lower legs which connected from knee, are the link L_2 with length 703 mm. Although the end point of link L2 called S_i points, they are not the picking point. The center of platform is picking point $P(x, y, z)$. Thus, the length between S_i and P point (L_P) is 62 mm. The moving platform can be assumed to be kinematics diagram as the picture shown below.

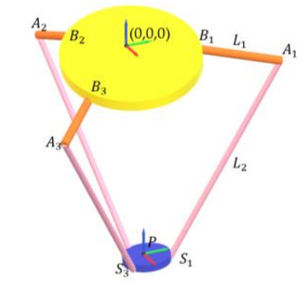


Fig. 2. The kinematics diagram

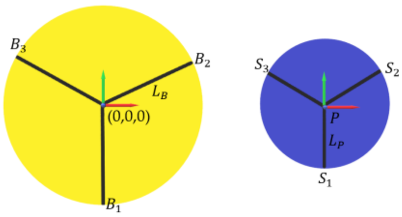


Fig. 3. Delta robot fix base details and moving platform details

Name	Meaning	Value (mm)
$\boldsymbol{L_B}$	Planar distance from {0} to servo motor	145
$\boldsymbol{L_1}$	Upper legs length	260
$\boldsymbol{L_2}$	Lover legs parallelogram length	703
$\boldsymbol{L_P}$	Planar distance from {P} to a platform vertex	62

Table 1 Delta robot fix length parameters

Because delta robot is 3-dof robot, the joint variables at servo motor B_i can be assigned as $\theta = \{\theta_1, \theta_2, \theta_2\}^T$. Thus, the end point which be called Cartesian variables, are $P = \{x, y, z\}^T$.

From the fixed-base, the Homogenous transform from origin position to B_i points as called ${}_0^1H_i$ are:

$$ {}_0^1H_1 = \begin{bmatrix} \cos 90 & -\sin 90 & 0 & L_B \cos 90 \\ \sin 90 & \cos 90 & 0 & -L_B \sin 90 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1-1} $$

$$ {}_0^1H_2 = \begin{bmatrix} \cos -30 & -\sin -30 & 0 & L_B \cos -30 \\ \sin -30 & \cos -30 & 0 & -L_B \sin -30 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1-2} $$

$$
{}_{0}^{1}H_3 = \begin{bmatrix} \cos 240 & -\sin 240 & 0 & L_B \cos 240 \\ \sin 240 & \cos 240 & 0 & -L_B \sin 240 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1-3}
$$

Each joint of servo motor must be controlled by θ_i. Each leg has been assigned rotation as picture below.

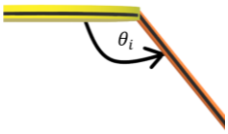


Fig. 4. Rotation of each legs

Then, the Homogenous transform from B_i points to A_i points as called ${}_{1}^{2}H_i$ are:

$$
{}_{1}^{2}H_i = \begin{bmatrix} \cos\theta_i & 0 & -\sin\theta_i & -L_1 \cos\theta_i \\ 0 & 1 & 0 & 0 \\ \sin\theta_i & 0 & \cos\theta_i & -L_1 \sin\theta_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}
$$

The lower legs are difficult to calculate the homogenous transform, because the angle of knee will relate to servo motor and {P} point. Thus, by assume that the platform must parallel with robot base, the platform calculation can be calculated before the lower legs by assume that the platform has be connected to the upper legs.

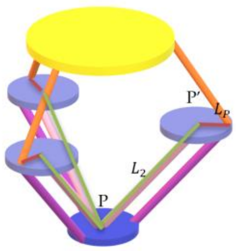


Fig. 5. Assuming platform connect to upper legs model

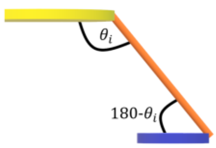


Fig. 6. Assume rotation of platform

The platform homogenous transform which be assumed to be ${}_{2}^{3}H_i'$ are:

$$
{}^{3}_{2}H'_i = \begin{bmatrix} \cos(180-\theta_i) & 0 & -\sin(180-\theta_i) & -L_P\cos(180-\theta_i) \\ 0 & 1 & 0 & 0 \\ \sin(180-\theta_i) & 0 & \cos(180-\theta_i) & -L_P\sin(180-\theta_i) \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Therefore,
$$
{}^{3}_{2}H'_i = \begin{bmatrix} -\cos\theta_i & 0 & \sin\theta_i & L_P\cos\theta_i \\ 0 & 1 & 0 & 0 \\ -\sin\theta_i & 0 & -\cos\theta_i & -L_P\sin\theta_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}
$$

From all Homogenous transform from above, it can calculate P'_i from the equation

$$
{}^{3}_{0}H'_i = {}^{1}_{0}H_i\,{}^{1}_{0}H_i\,{}^{3}_{2}H'_i = \begin{bmatrix} \{R_i\} & P'_i \\ \{0\} & 1 \end{bmatrix}
$$

Because the end point of delta robot does not care rotation matrix R_i; therefore, the point P'_i are:

$$
P'_1 = \begin{bmatrix} 0 \\ -(L_1\cos\theta_1 + L_B - L_P) \\ -L_1\sin\theta_1 \end{bmatrix} \qquad P'_2 = \begin{bmatrix} \frac{\sqrt{3}}{2}(L_1\cos\theta_2 + L_B - L_P) \\ \frac{1}{2}(L_1\cos\theta_2 + L_B - L_P) \\ -L_1\sin\theta_2 \end{bmatrix}
$$

$$
P'_3 = \begin{bmatrix} -\frac{\sqrt{3}}{2}(L_1\cos\theta_3 + L_B - L_P) \\ \frac{1}{2}(L_1\cos\theta_3 + L_B - L_P) \\ -L_1\sin\theta_3 \end{bmatrix}
$$

From figure 6, the P'_i will be link with lower legs and end at the point P. Thus, the point P can be calculated with sphere equation:

$$
(x-a)^2 + (y-b)^2 + (z-c)^2 = r^2
$$

Using $r = L_2$ and $\{x, y, z\}$ as $\{P'_i\}$ set, finally it can be:

$$
-2(ax_i + by_i + cz_i) + (a^2 + b^2 + c^2) - {L_2}^2 + ({x_i}^2 + {y_i}^2 + {z_i}^2) = 0 \tag{4}
$$

Assume $(a^2 + b^2 + c^2)$ parameters as A and ${L_2}^2 - ({x_i}^2 + {y_i}^2 + {z_i}^2)$ is variable as B_i. Thus,

$$
-2(ax_1 + by_1 + cz_1) + A = B_1
$$
$$
-2(ax_2 + by_2 + cz_2) + A = B_2
$$
$$
-2(ax_3 + ay_3 + az_3) + A = B_3
$$

After solved the sphere equation, point P will be release at $[a, b, c]^T$

3.2 Inverse Kinematics (IK) Solution

From the sphere equation (4) at above, it can be proved that each leg of delta robot can be solved independently. Thus, the equations can be changed to geometry form. The independent scalars of Inverse Kinematics equations are the form:

$$E_i \cos\theta_i + F_i \sin\theta_i + G_i = 0 \qquad i = 1,2,3$$

By set square parameters to be variable as:

$$P = a^2 + b^2 + c^2$$

$$N = L_B - L_P$$

$$M = N^2 + {L_1}^2 - {L_2}^2$$

By input position P_i' to the sphere equation (4), after derived the equation, each leg's equation will be shown as:

Equation 1st Leg:

$$2L_1(N + b)\cos\theta_2 + 2cL_1 \sin\theta_1 + P + M + 2bN = 0$$

Therefore,

$$E_1 = 2L_1(N + b),\ F_1 = 2cL_1, \text{ and } G_1 = P + M + 2bN$$

Equation 2nd Leg:

$$L_1\left(2N - \sqrt{3}a - b\right)\cos\theta_2 + 2cL_1 \sin\theta_2 + P + M - \sqrt{3}aN - bN = 0$$

Therefore,

$$E_2 = L_1\left(2N - \sqrt{3}a - b\right),\ F_2 = 2cL_1, \text{ and } G_2 = P + M - \sqrt{3}aN - bN$$

Equation 3rd Leg:

$$L_1\left(2N + \sqrt{3}a - b\right)\cos\theta_2 + 2cL_1 \sin\theta_3 + P + M + \sqrt{3}aN - bN = 0$$

Therefore,

$$E_3 = L_1\left(2N + \sqrt{3}a - b\right),\ F_3 = 2cL_1, \text{ and } G_3 = P + M + \sqrt{3}aN - bN$$

From the Equation $E_i \cos\theta_i + F_i \sin\theta_i + G_i = 0$, if transfer $\sin\theta_i = \frac{2\tan\frac{\theta_i}{2}}{1+\left(\tan\frac{\theta_i}{2}\right)^2}$, and $\cos\theta_i = \frac{1-\left(\tan\frac{\theta_i}{2}\right)^2}{1+\left(\tan\frac{\theta_i}{2}\right)^2}$ and assume that $t = \tan\frac{\theta_i}{2}$, then the geometry equation will be:

$$E_i \frac{1 - t^2}{1 + t^2} + F_i \frac{2t}{1 + t^2} + G_i = 0$$

$$(G_i - E_i)t^2 + 2F_i t + (G_i + E_i) = 0$$

Thus, it can solve t from quadratic formula $t = \frac{-F_i \pm \sqrt{{E_i}^2 + {F_i}^2 - {G_i}^2}}{(G_i - E_i)}$. Finally, inverse kinematics can be solved by:

$$\theta_i = 2\tan^{-1} t$$

3.3 Mechanical Design

The design of the delta robot starts with the 3 spindle parts. Servo motors are considered as an important factor in the structure. Thus, the AC servo motor is selected in the system. From the Fig. 7 has shown the structure of the servo motor, belt and gear box set. The design must consider the size of the motor to support torque. The position of the gear box must suit in the working area of the Delta robot. The simulation of motor assembly into upper arm and belt can show that the assembly of the upper arm fitting set to be appropriate. Thus, when the equipment is assembled, it will be suitable and fit with all work.

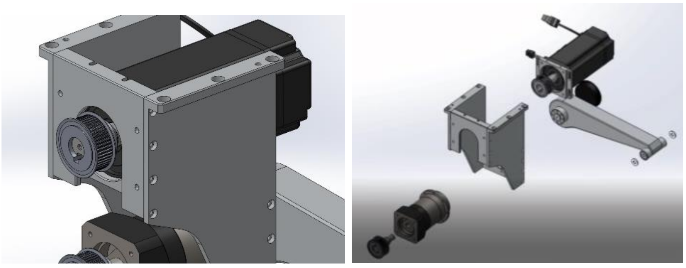


Fig. 7. Structural position of servo and gear box and assembly of motor to belt

Fig. 8. Top cover of delta robot designed by Solidwork

Cover structure is considered an important part to prevent danger while the robot is working. It can protect motor while driving in high speed. Moreover, it can make robot design look beautiful because when the prototype completed, the delta robots must be built for sell in the future. The whole design of the Delta robot has been created and simulated by Solidwork program before construct to be the actual robot. The robot consists of 3 main axes with a separated upper arm. The bottom arms are connected from the upper arm at the middle position. There is a motor at the top-center of robot to assist rotation for control center direction when robot is capturing workpieces.

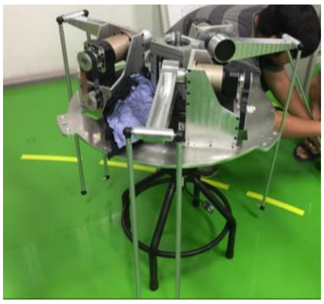


Fig. 9. Assembly servo motor to robot

Fig. 10. Complete Delta Robot

3.4 Electrical and Control Design

Functions of delta robot have integrated robot controllers, motion controllers and servo drivers in one unit that are highly flexible and reliable. Communication protocols are supported for fast integration and other peripherals that various for robot control modules in different applications. In addition, the control driver is easy to extend the motor drive axis. Moreover, the system has supported up to 5 programming languages with the standard IEC 61131-3 and blocks the operation of the PLCopen. One of the languages is a DRL language, which is used for developing android applications and specific skill functions as needed, and supports G Code in programming code for path planning.

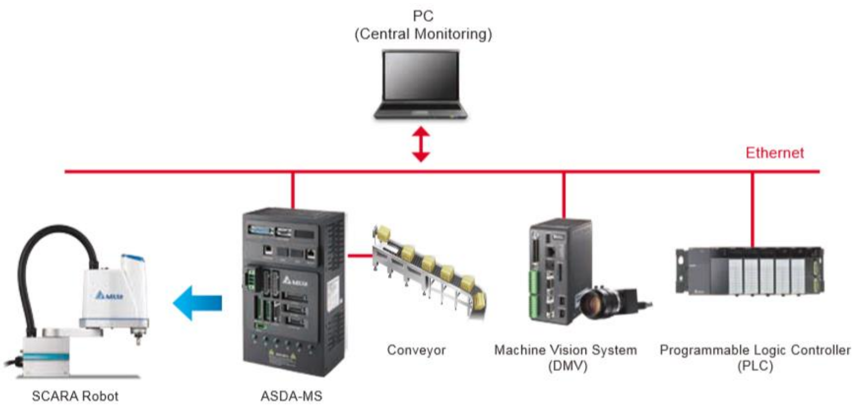


Fig. 11. Wiring Diagram of 4 Servo Motor

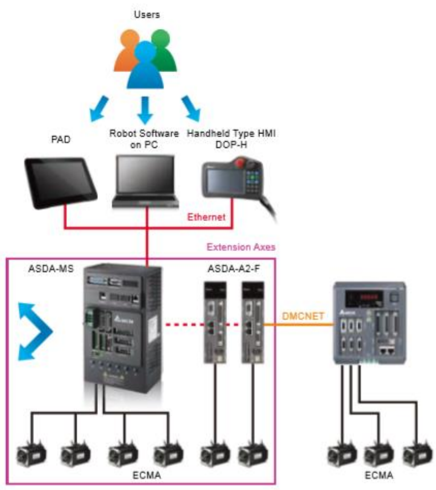


Fig. 12. Connection system to other devices

4 Experiment and Results

After the structure of Delta robot is built and completed programming, testing result is implemented. Students can use this experiment to evaluate the mathematical model and practice for program testing.

In testing, the Delta robot must carry a pencil to draw on a paper for test control position. The error results are compared between programing control input and the real output. The result comes out in different speed as follow:

Result	15% speed	20% speed	40% speed
Error in XY (mm)	3 mm	3 mm	4 mm
% of Error	1.34%	1.34%	1.41%

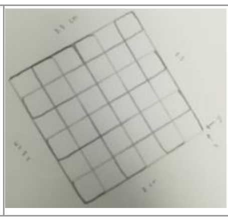
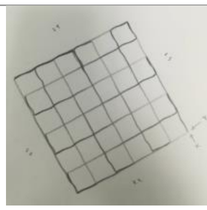
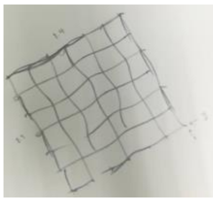
Test result			

Table 2 Delta robot fix length parameters

5 Applied for learning

There are many robot applications which applied in industrial automation such as packaging, pick, and place. Human can work for good and accurate positioning which is required the skills and experience of the working tasks. However, the important purpose is to reduce the problem of error in the production line and increase the performance of yield rate. In order to eliminate such problems and reduce time of working, the invention of robots, which replaced human in faster pick and place products, is a new learning media education. Therefore, the study of Delta robot is an interesting topic that the robot has a specific design, calculation work area and working mechanism. Therefore, researchers have the objectives of creating experimental media for the robot with complex designs to obtain higher efficiency, and can be used in automation production line. For the prototype of the training set, it can allow students to study and test the robot. The project base learning by using Delta Robot can be applied to studied coursework by designing the mechanisms and controller. In learning practice, student can study the forward/inverse kinematic model. Students can see results when they changed the parameter of model and students are able to do the experiment with the actual work. This literature is focusing on delta robot and it is useful for those students and researchers who are interested in robotic fields.

6 Conclusion

This project has shown the delta robot was developed and it can be used for a project base learning to study the fundamental of delta robot. This project can be applied for education to be more understanding on the mathematic of robot model. Moreover, it can be used for adapting or applying to other robot types. It also can study how to develop robot as a product for industrial purpose. However, the robot prototype still has large error result. It cannot be used in industrial purpose which requires error less than 0.1 mm. Therefore, the robot must be improved in accuracy for more efficiency.

7 Acknowledgment

We would like to thank the National Science and Technology Development Agency (NSTDA) for financial support to this research and provide the special expertise for comments and advising research work.

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