# STRUCTURE AND CONTROLLER DESIGN OF 6-AXIS VERTICAL ARTICULATED ROBOT

**Sermsiri Chareonkid**
Department of Mechanical Engineering
Mahanakorn University of Technology
Bangkok
**Anan Kongyoo**
Design Engineering Department
Mitsubishi Elevator Asia Co., Ltd.
Chonburi
**Kittisak Yongsiri**
Department of Mechanical Engineering
Mahanakorn University of Technology
Bangkok

*A low-cost 6-axis vertical articulated robot is designed and built as a demonstration set of fundamentally studies of robot design, kinematics and control system. Aluminum and light material are used as material for robot structure. Stepping motors are used to power robot motion. Robot can be controlled by both joint and position levels commands. Controller cards are developed to control the motors from PC via a printer interface card. The accuracy and precision of robot are investigated by applying playback control routines for both point to point and contour movements. The experiment illustrates promise results as a low cost demonstration robot.*

## 1. Introduction

Robotics is a course that has been being taught in university for both undergraduate and graduate levels in engineering for many years. Several academic institutions provide just theoretical courses without any practical work in laboratory because of budget constraint according to economic crises. A robot with controller may cost at least 200,000 bahts and must be imported. This paper presents an alternative way of studying robotics by building a robot as a laboratory-based equipment. Three major benefits are that

a) the cost is as low as 25,000 bahts.
b) student acquired hand-on experiment with robot.
c) the expertise is developed.

The robot designed and built in the paper is vertical-articulated type which is commonly employed in industries. Her structure and controller are designed with low cost and laboratory-based in mind. The structure is made from local light-weight material, i.e. aluminum. The control program is developed on Turbo C++ which can be conveniently interfaced between software and hardware. The justification of the system built is by operating cycle-control routines for both point-to-point and contour movements. The controller is designed by implementing simple electronic components in order to control and drive stepping motors which power the robot movements.

## 2. Formulation

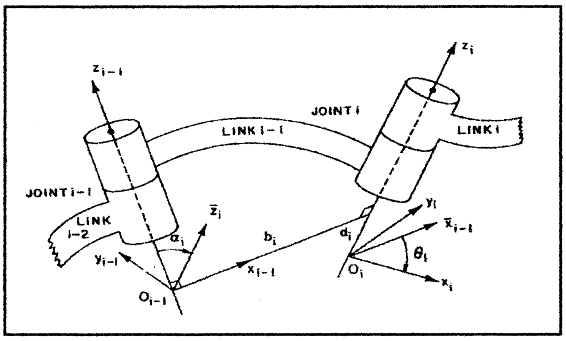



**Figure 1** D-H representation

Consider the situation depicted above in Figure 1. Let $Z_{i-1}$ and $Z_i$ represent fixed axes at either end (joint) of link i-1, above which or along which links i-1 and i move, respectively. axis $X_{i-1}$ be defined from $Z_{i-1}$ to $Z_i$ and perpendicular to both.

$O_{i-1}$ denote the point of intersection of axes $Z_{i-1}$ and $X_{i-1}$.

$Y_{i-1}$ represent the unique axis that together with $X_{i-1}$ and $Z_{i-1}$ completes a right-hand Cartesian coordinate system.

$Z_i$ represent a vector from $O_{i-1}$ parallel to $Z_i$.

$X_{i-1}$ represent a vector from $O_i$ parallel to $X_{i-1}$

The following four ordered operations completely specify the configuration of the frame i coordinate system relative to the frame i-1 coordinate system:

a) A constant *twist* of $\alpha i$ degrees about axis $X_{i-1}$ of $Z_{i-1}$ into $Z_i$, : $T_{ai}$
b) A constant *displacement* of $b_i$ units along $X_{i-1}$ from $Z_{i-1}$ to $Z_i$, : $T_{bi}$
c) A *rotation* of $\theta i$ degrees about $Z_i$ of $X_{i-1}$ into $X_i$, with :$T_{ci}$

d) An *offset* of $d_i$ unit along $Z_i$ from the $X_{i-1}, Z_i$ intersection to $O_i$, : $T_{di}$

The overall D-H coordinate transformation matrix is then given by

$$T^{i}_{i-1} = T_{ai} T_{bi} T_{ci} T_{di} = \begin{bmatrix} c\theta i & -s\theta i & 0 & b_i \\ c\alpha i s\theta i & c\alpha i c\theta i & -s\alpha i & -d_i s\alpha i \\ s\alpha i s\theta i & s\alpha i c\theta i & c\alpha i & d_i c\alpha i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For this robot, following parameters is obtained :

**Table 1** Robot parameters

| Link | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| $\alpha i$ | 0 | +90 | 0 | +90 | -90 | +90 |
| $b_i$ | 0 | b | e | 0 | 0 | 0 |
| $\theta i$ | $\theta 1$ | $\theta 2$ | $\theta 3$ | $\theta 4$ | $\theta 5$ | $\theta 6$ |
| $d_i$ | h | 0 | 0 | f | 0 | d |

General 6-axis homogeneous transformation matrix to base is represented as follow :

$$T_0^6 = \left[\begin{array}{ccc:c} s_x & a_x & n_x & p_x \\ s_y & a_y & n_y & p_y \\ s_z & a_z & n_z & p_z \\ \hdashline 0 & 0 & 0 & 1 \end{array}\right]$$

As we substituted parameters from Table 1 in D-H coordinate transformation matrix and compared with 6-axis homogeneous transformation matrix to base this research is represented as follow :

$$p_x = d\,(c_1c_{23}c_4s_5 + c_1c_5s_{23} + s_1s_4s_5) + fc_1s_{23} + ec_1c_2 + bc_1$$

$$p_y = d(s_1c_{23}c_4c_5 + s_1c_5s_{23} - c_1s_4s_5) + fs_1s_{23} + ec_1c_2 + bs_1$$

$$p_z = d(s_{23}c_4s_5 - c_5c_{23}) - fc_{23} + es_2 + h$$

$$s_x = c_1c_{23}c_4c_5\,c_6 - c_1c_{23}s_4\,s_6 - c_1s_{23}s_5c_6 + s_1s_4c_5c_6 + s_1c_4s_6$$

$$s_y = s_1c_{23}c_4c_5\,c_6 - s_1c_{23}s_4\,s_6 - s_1s_{23}s_5c_6 - c_1s_4c_5c_6 - c_1c_4s_6$$

$$s_z = s_2c_3c_4c_5c_6 - s_2c_3s_4\,s_6 + c_2s_3c_4c_5c_6 - c_2s_3s_4s_6 + s_5c_2s_3s_6 + s_5c_6s_2s_3$$

$$a_x = -c_1c_{23}c_4c_5s_6 - c_1c_{23}s_4\,s_6 + c_1s_{23}s_5\,c_6 - s_1s_4c_5s_6 + s_1c_4c_6$$

$$a_y = -s_1c_{23}c_4c_5s_6 - s_1c_{23}s_4\,c_6 + s_1s_{23}s_5\,s_6 + c_1s_4c_5s_6 + c_1c_4c_6$$

$$a_z = -s_2c_3c_4c_5s_6 - s_2c_3s_4\,c_6 - c_2s_3c_4c_5s_6 - c_2s_3s_4c_6 - s_5c_2s_3s_6 + s_5s_6s_2s_3$$

$$n_x = c_1c_{23}c_4s_5 + c_1s_{23}c_5 + s_1s_4s_5$$

$$n_y = s_1c_{23}c_4s_5 + s_1s_{23}c_5 - c_1s_4s_5$$

$$n_z = c_4s_5s_2c_3 + c_4s_5c_2\,s_3 - c_5c_2c_3 - c_5s_2s_3$$

All above equations are forward kinematic equations. After that find inverse kinematic equations. Results are following :

$$\theta_1 = A\tan 2\ \frac{P_{yw}}{-P_{xw}}$$

$$\theta_2 = A\tan 2\ \frac{[(P_z - h)(e+f\,s_3)] + [(P_{xw}c_1 + P_{yw}s_1 - b)\,(f\,c_3)]}{[-(P_z - h)(f\,c_3)] + [(P_{xw}c_1 + P_{yw}s_1 - b)\,(e+f\,s_3)]}$$

$$\theta_3 = A\tan 2\ \frac{a}{\pm\sqrt{1-a^2}} \quad ,(\text{both } \theta_3 \text{ and } (180^{o} - \theta_3))$$

$$\text{when } a = (P_{wz} - h)^2 + (P_{xw}c_1 + P_{yw}s_1 - b)^2 - e^2 - f^2$$

$$\theta_4 = A\tan 2\ \frac{(a_x\,s_1 - a_y\,c_1)}{(a_x c_1\,c_{23} + a_y\,s_1\,c_{23} + a_z\,s_{23})} \quad \text{or } \theta_4 \pm 180^{o}$$

$$\theta_5 = A\tan 2\ \frac{-\sqrt{(a_x s_1 - a_y c_1)^2 + (a_x c_1\,c_{23} + a_y\,s_1\,c_{23} + a_z\,s_{23})^2}}{a_x c_1\,c_{23} + a_y\,s_1\,c_{23} - a_z\,s_{23}}$$

$$\text{or } \theta_5 \pm 180^{o}$$

$$\theta_6 = A\tan 2\ \frac{-(s_xc_1s_{23} + s_ys_1s_{23} - s_zc_{23})}{-(-n_xc_1s_{23} - n_ys_1s_{23} + n_zc_{23})} \text{ or } \theta_6 \pm 180^{o}$$

$$c_1 = \cos\theta_1\ ,\ s_1 = \sin\theta_1\ ,\ c_{12} = \cos(\theta_1 + \theta_2)\ ,\ s_{12} = \sin(\theta_1 + \theta_2)$$

## 3. Mechanical Design of the Robot

The structure of the robot is carefully designed to fulfill the requirements. Six main features in design criteria are specified as listed below.

3.1 Material used is aluminum because of its light weight. Inertia and power supplied can be reduced.

3.2 Sweep angles

The robot has 6 degrees of freedom as illustrated in Figure 2. The sweep angles correspond to the 6 joints are shown in Table 2.

**Table 2** Sweep angles of the robot

| Names | Joints | Sweep angles(degree) |
|---|---|---|
| Arm sweep | 1 | 300(-150 to +150) |
| Shoulder swivel | 2 | 80 (-70 to +10) |
| Elbow sweep | 3 | 75 (-30 to +45) |
| Yaw sweep | 4 | 180 (-90 to +90) |
| Pitch sweep | 5 | 90 (-90 to 0 ) |
| Roll sweep | 6 | 360 (-180 to +180) |

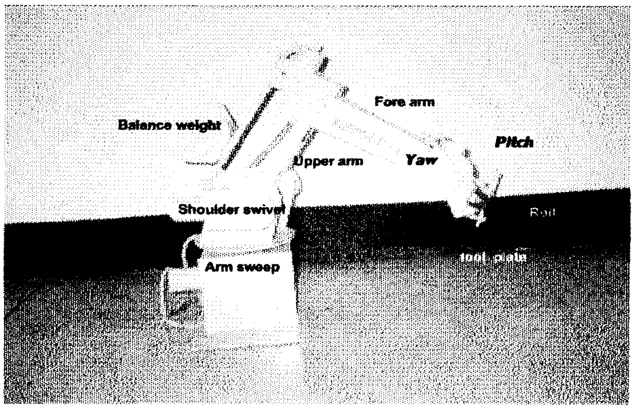
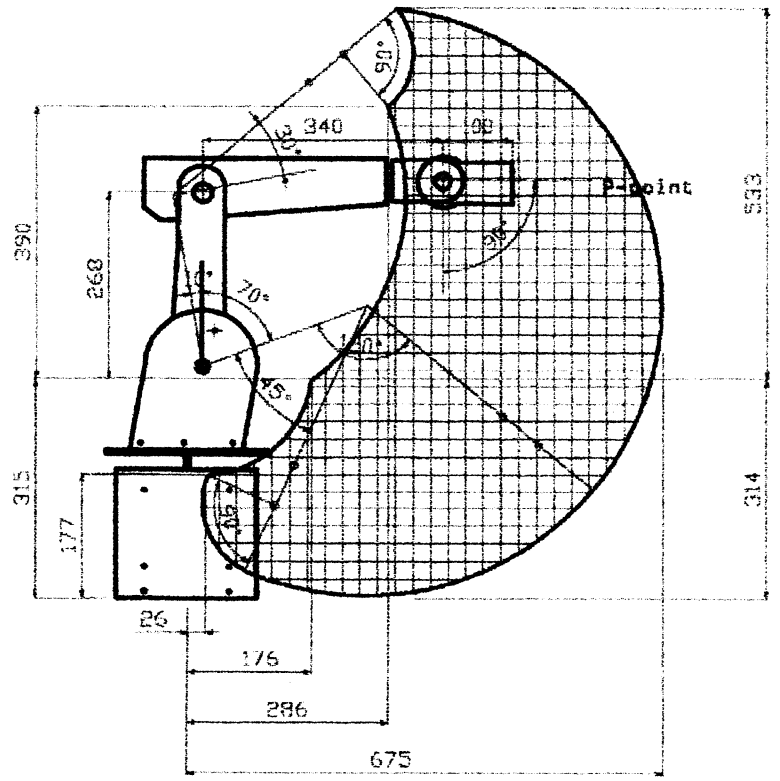



**Figure 2** Manipulator structure

3.3 Working volume of the robot

The robot has working volume as show in Figure 3.



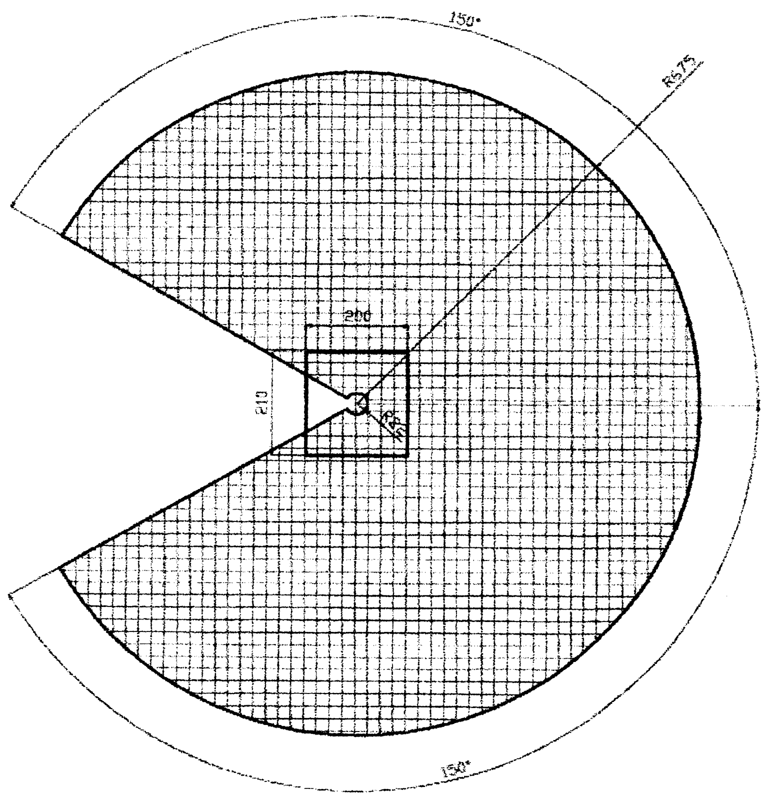




**Figure 3** Working volume of the robot