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APPLICATION OF DENAVIT HARTENBERG METHOD IN SERVICE ROBOTICS

Erik Prada
Technical University of Kosice, Faculty of Mechanical Engineering, Letna 9, Kosice, Slovak Republic, EU, erik.prada@tuke.sk (corresponding author)
Srikanth Murali
Technical University of Kosice, Faculty of Mechanical Engineering, Letna 9, Kosice, Slovak Republic, EU, srikanth.murali@tuke.sk
Ľubica Miková
Technical University of Kosice, Faculty of Mechanical Engineering, Letna 9, Kosice, Slovak Republic, EU, lubica.mikova@tuke.sk
Jana Ligušová
KYBERNETES, s.r.o., Omska 14, Kosice, Slovak Republic, EU, jana.ligusova@kybernetes.sk

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Abstract: This work focuses primarily on the D-H method, as one of the most important methods used in the process of designing robotic structures. In the introduction, the history of the D-H method and its general use is briefly mentioned. In the following section, the algorithm for applying D-H in the form of mathematical formalism is explained. In this part, the individual steps of creating transformational relationships are explained in more detail. The next chapters deal in more detail with individual application types within service robotics. The first type deals with the application deployment of the mobile robotic platform, the second deals with the mobile humanoid robotic structure, the other deals with the four-legged robotic mechanism and the last type with the application of the robotic arm.

1 Introduction

With the fast advancement of robot innovation, service robots are slowly showing up in a wide area to the public. Service robots are the one which will perform work in a fully automatic or semi-automatic way for a human or another equipment for which the service robot is made for. Scientific researchers from various parts of the globe are investing their time and effort towards the control and intelligent algorithm of the service robots. One of the important elements of a service robot is its arm also known as the manipulator [1]. It is a significant characteristic of the service robot to have a flexible arm which has to be controlled as per its requirement [2]. Kinematics is the area where the control of the arm is designed to serve its purpose and analyse the arm movement to be effective according to the mechanical structure of the robot.

The robot manipulator is classified according to the kinematic structure as serial, parallel and hybrid manipulator. In serial manipulator, each individual link is connected to other link in series by different joints, usually prismatic or revolute joints. It is also called open loop chain. Parallel manipulator on the other hand consists of several closed loop chains where one joint in the chain is actuated and the other joints are passive. A hybrid manipulator combines the serial and parallel manipulator. The above image (Figure 1) shows the classification of manipulator according to their kinematic structure. We are interested towards the serial manipulator in this document and we will dive deep into it. As mentioned previously, the serial manipulator comprises of several links connected in series. One end of the arm is attached to the ground and the other end of the arm is made to move freely in space. The fixed arm is known as base and in the free end a mechanical hand or gripper is attached. The important aspect for a robot to perform its task is the establishment of the location of end effector relative to its base. This method of establishing the location offend effector with respect to the base is known as position analysis problem. There are two subdivision for solving the position analysis problem. One is direct position method or direct kinematics method. In this method, the goal is to find the location of the end effector in which the joint variables are given. The other is the inverse position or inverse kinematics method in which the location of end effector is known, and the aim is to find the joint variables that are needed to bring the manipulator to its required position [3-6].

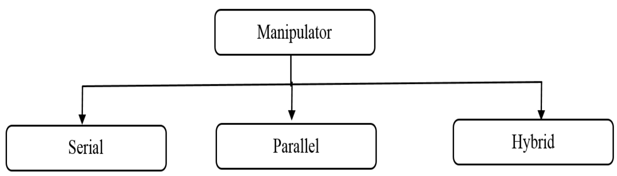

Figure 1 Classification of Manipulator according to kinematic structure

There are many methods available to deal with the Kinematics of the manipulator. The best among the available method has to be chosen with due to the robot's mechanical structure. Most successful and widely used methods include numerical method, geometry method, optimization algorithm and the vector algebra method. The numerical method refers mainly to the Denavit-Hartenberg method [7]. It is also called as 4x4 matrix method or simply D-H method. Jacques Denavit and Richard Hartenberg in 1955 introduced this method in order to standardize the coordinate frames for spatial linkages. This method is a consistent and short description depicting the kinematic relations among the links connected by 1 degree-of-freedom lower pair joints, usually, rotational and prismatic joints. Nowadays, various other methods were introduced by this method still shows to be efficient for several specific movements of the robotic manipulator. We will be looking into this method and then some of the areas where this method is used in positioning the robotic manipulator in achieving their requirements [8-10].

2 Denavit Hartenberg Method

In this method, the coordinate frames are attached to the joints between two links such that one of the transformations is associated with the joint [Z], while the second is associated with the link [X]. For a serial robot consisting of n links, the coordinate transformations from the kinematic equations of the robot are given by (1),

$$[T] = [Z_1][X_1][Z_2][X_2] \ldots [Z_{n-1}][X_{n-1}][Z_n][X_n] \qquad (1)$$

where [T] denotes the transformation locating the end-link. Below is an image showing the four parameters involved in the D-H convention.

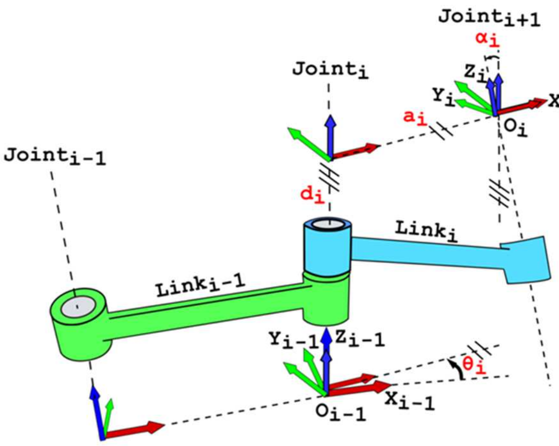

Figure 2 Four parameters of D-H convention [7]

From the above image we can depict that the four parameters associated with the D-H convention which are represented in red colour. They are θ_i, d_i, a_i, α_i. Using these four parameters we can translate the coordinates from O_{i-1}, X_{i-1}, Y_{i-1}, Z_{i-1} to O_i, X_i, Y_i, Z_i. These four parameters are known as D-H parameters and below is the process for achieving the transformations. The variables denote the following:

- *d*, offset along the previous Z axis to the common normal,
- θ, angle from previous Z, from old X to new X,
- *a*, length of the common normal (also denoted as *r*). Assuming revolute joint, this is the radius about previous Z,
- α, angle about common normal, from old Z axis to new Z axis.

The D-H parameters gives a standard way to write the manipulator's kinematic equation, especially for serial manipulators. This can be done by using a matrix (2) to express the position and orientation of one body with respect to another body.

$$^{n-1}T_n = \begin{bmatrix} \cos\theta_n & -\sin\theta_n\cos\alpha_n & \sin\theta_n\sin\alpha_n & a_n\cos\theta_n \\ \sin\theta_n & \cos\theta_n\cos\alpha_n & -\cos\theta_n\sin\alpha_n & a_n\sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

This can be written as (3):

$$^{n-1}T_n = \begin{bmatrix} & R & & T \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

where: R is the 3x3 matrix representing the rotation and T is 3x1 matrix representing translation.

2.1 *Advantages of D-H method*

Some of the advantages of the D-H convention are as follows:

- Main aspect of D-H convention is the roto-translation in terms of only 4 variables for each individual link when compared with the canonical form involving 6 variables (3 for translation and 3 for rotation).
- It is very easy and convenient to get the transformation of number of links attached in series by multiplying the transformation series rather than calculating manually by basic geometry method [11-12].
- Faster convergence of estimated states is achieved in a least-squares technique by employing D-H parameters to it. Simply saying, this will help in the reduction of error faster [11-12].
- D-H parameters are more consistent and simpler when compared to Product of Exponential (POE) parameters with respect to serial link robots [13].
- Minimal representation is achieved with D-H parameters. It is nice when worked with linear algebra computations.
- D-H based algorithm model acts as an efficient tool for sub-problems and also for real-time inverse kinematics solution for the trajectory of serial link robots [2].

3 Applications of D-H Method

3.1 Body Activity Interaction for a Service Robot

In the field of intelligent robots, the interaction with human body plays a major role. Body Activity Interaction in a service robot [13] works in a way to realize the body activities and interact accordingly. Microsoft Kinect is utilized to capture the body movements and the action recognition module provides input signals depending on the captured movements programmed into it. The field data from Kinect is capable of tracking the 20 bones of human body and by processing this data we can obtain the recognition action for the robot movement. Some of the field data includes tracking the human shoulder, wrist joints, elbows, etc. Below image (Figure 3a) shows the robot's structure and the motion control of the robotic manipulator (Figure 3b). The Kinematic model consists of 6 degree of freedom right arm of the robot consisting of the links and it is solved with the help of D-H convention. The parameters used for solving the D-H convention are listed in the table (Table 1).

Figure 3 a) Structure of the robot [13]

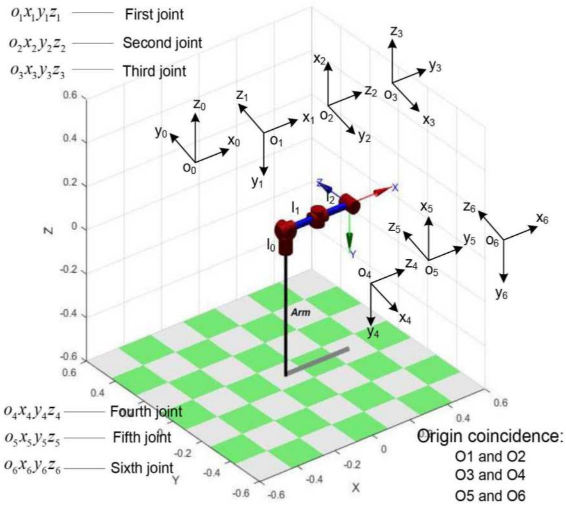

Figure 3 b) Motion control of the arm [13]

From the table, we can depict that, the θ_i is the i-1th joint angle and α_i is the i-th torque angle. Whereas the offset link is denoted as di and ai is the length of the link. MATLAB Robotics Toolbox is used to control the kinematics motion planning of the robotic arm which are used to design the hand shaking and hand waving motions. Figure 4 shows the planning of the variations in joint angle for performing the handshaking motion computed in MATLAB [13].

Table 1 Denavit-Hartenberg parameters for the robotic manipulator [13]

i	θ_i	α_i	a_i (m)	d_i (m)
x1	θ_1	-90º	0	0.065
2	θ_2 - 90º	-90º	0	0
3	θ_3 + 90º	90º	0	0.170
4	θ_4	-90º	0	0
5	θ_5 - 90º	90º	0	0.169
6	θ_6 + 90º	0º	0	0

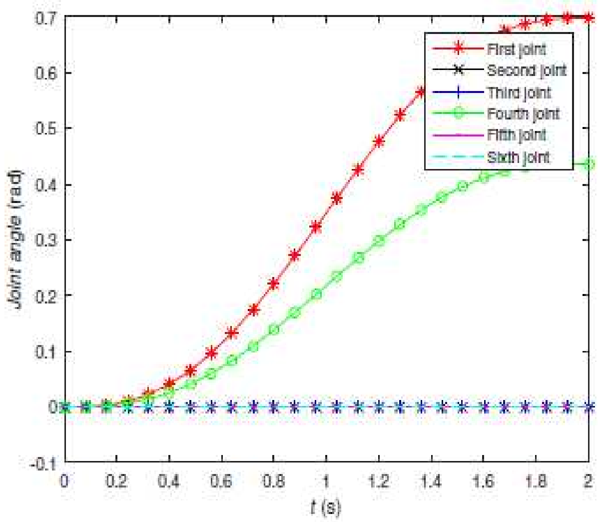

Figure 4 a) Right arm lifting [13]

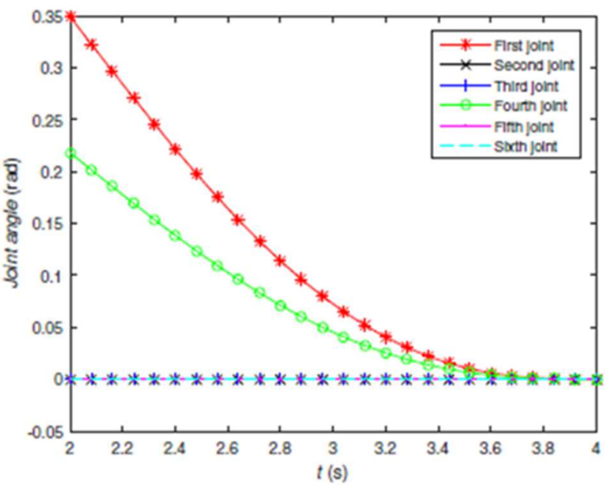

Figure 4 b) Right arm lowering [13]

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From the above images we can derive that the positive values are obtained for the first and the fourth joint meaning that rotation about fixed degrees in fixed direction of the shoulder and elbow joints thus extending the right arm. For lowering the right arm, the first and fourth joint are taking the negative values [13].

3.2 Mobile Humanoid Robot

Mobile humanoid robot [14] has been invented to assist elderly people. The robot is constructed with a visual sensor for recognizing objects. At the lower part of the robot is placed the Laser Range Finder which helps to detect obstacles. Once the object is identified, the robot moves toward it and then it uses the grasping motion to hold the object. It can also be used in hospitals or homes to work actively with the humans in real environment. Below image (Figure 5a) shows the robot design and the image (Figure 5b) represents the kinematic mechanism of the robot manipulator.

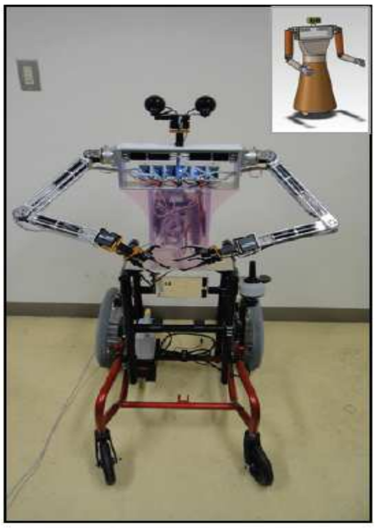

Figure 5 a) Showing the mechanical design of mobile Humanoid robot [14]

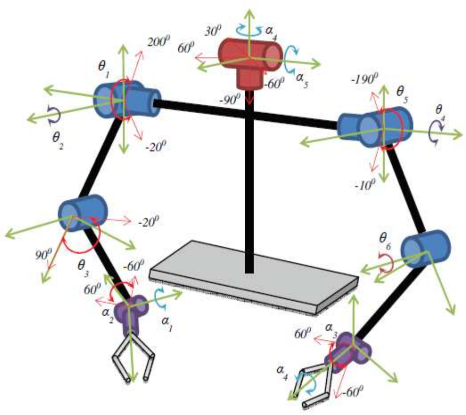

Figure 5 b) Showing the kinematics structure of mobile Humanoid robot [14]

Table 2 Denavit-Hartenberg parameters for the mobile service robot [14]

Joint, i	α_i	a_i	d_i	θ_i
0A	90°	0	d_1	θ_1
B	0	a_1	0	θ_2
C	0	a_2	0	θ_3
D	0	0	0	Gripper

The table (Table 2) shows the D-H parameter used in solving the kinematics of the robot and the matrix (4) representation of the D-H convention is given as follows:

$$T_4^0 = \begin{bmatrix} c_1\, c_{23} & -c_1\, s_{23} & s_1 & c_1(a_3\, c_{23} + a_2\, c_2) \\ s_1\, c_{23} & -s_1\, s_{23} & -c_1 & c_1(a_3\, c_{23} + a_2\, c_2) \\ s_{23} & c_{23} & 0 & a_3\, s_{23} + a_2\, s_2 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

From the D-H Matrix we can derive that the orientation of the end effector was represented by the first three columns and the position of the end effector is represented by the last column such that, in terms of joint angles we can derive both the position and orientation of the end effector [14].

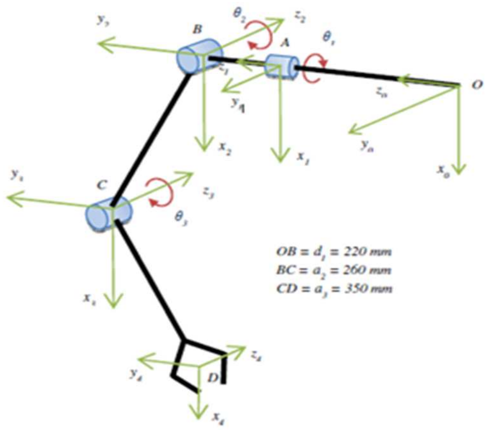

Figure 6 Manipulator for D-H convention [14]

3.3 Quadruped robot

Quadruped [15] robots are used to mimic the animal waling gait. It has four legs instead of wheels. The main advantage is that they can be used to walk on terrain and extremely hard surfaces. This is the main difference among the quadrupeds when compared with that of the wheeled vehicles where the vehicles with wheel will be stuck in place of the obstacles on a rough path and the quadrupeds can easily move pass the obstacles by adjusting their height. The D-H convention is used for deriving the kinematic solutions and thus these solutions can be used for simulating the movement using 3D software. The robot can be controlled via an Android application using the Bluetooth Technology. The robot hosts six types of movements: forward, backward, left walking, right walking, rotation in clockwise and anti-clockwise direction. Obstacles within the range of 300 cm are identified with the help of ultrasound sensors. The robot is capable of moving in parallel towards an identified obstacle in a way to avoid colliding with it. Each of the four legs of the quadruped has 2 degrees of freedom which resembles the hip and knee joints of the leg and in total it has 8 degrees of freedom. In this case, the following are the D-H parameters associated with the quadruped movement: the link length is represented as a and the link twist as A. The link offset as and the angle of joint as T. Below is the D-H parameters table (Table 3) and the matrix (5) representing the D-H convention [15].

Table 3 D-H parameters for quadruped robot [15]

Link	a	A	d	T
L_1	a_1	90	0	t_1
L_2	a_2	0	0	t_2

$$T = \begin{bmatrix} c_1c_2 & -c_1s_2 & s_1 & c_1(a_1 + a_2c_2) \\ s_1c_2 & -s_1s_2 & -c_1 & s_1(a_1 + a_2c_2) \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5)$$

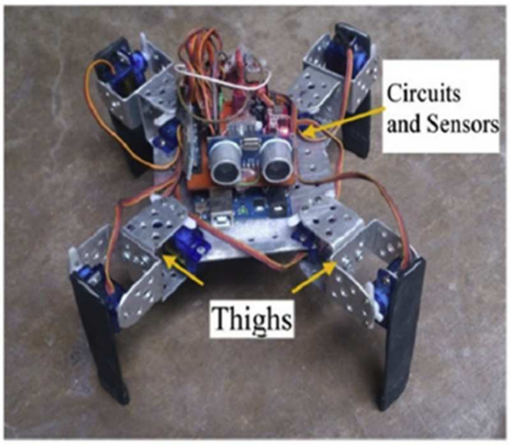

Figure 7 a) Quadruped robot - top view [15]

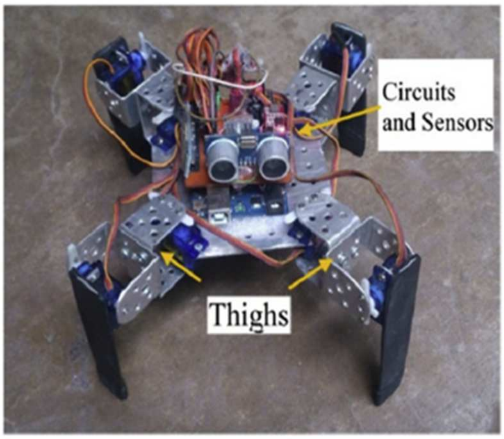

Figure 7 b) Quadruped robot – front view [15]

3.4 Robotic Arm

The robotic arm [16] here discussed is used for pick and place operations. The robot is provided with the voice recognition and image processing capabilities. The simulation of the mechanical structure in forward kinematics is carried out in MATLAB and the design is using the Denavit-Hartenberg convention. The serial link manipulator is achieved by the connection of the links with the joints in a sequential manner and thus it is analysed with the D-H parameter method. By this, we can obtain the result in a matrix where the Cartesian position of the end effector is expressed in terms of the joint coordinates. The D-H parameter is shown in the table (Table 4).

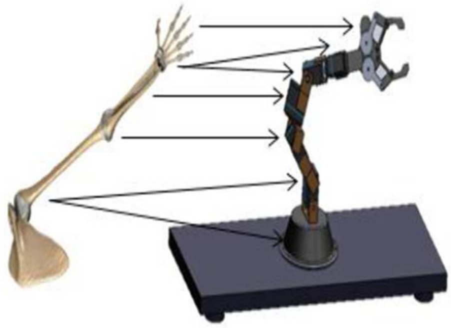

Figure 8 a) Design of the robot arm [16]

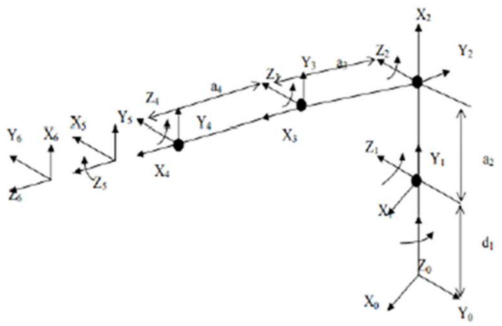

Figure 8 b) Kinematic analysis of the arm [16]

Table 4 D-H parameters of robot arm [16]

Joint, i	α_{i-1}	d_i	θ_i	a_{i-1}
1	90°	d_1	θ_1	0
2	0°	0	θ_2	a_2
3	0°	0	θ_3	a_3
4	90°	0	θ_4	a_4
5	90°	0	θ_5	0
6	0°	d_6	θ_6	0

The arm of the robot is constructed in resemblance to the human arm joints like shoulder, elbow and wrist. Each of the elbow joints has a single degree of freedom and the wrist can project in two planes namely, Rolland pitch, as a result of providing more flexibility for the end effector in terms of manipulation of the object [16].

4 Conclusions

The Denavit-Hartenberg method is one of the effective and simple way to derive the kinematics of a robot mechanism. There are a number of applications apart from the topics discussed in this document that involves the use of Denavit-Hartenberg conventions. Even though, a number of methods are available, the D-H method is still one of the widely used method to solve the kinematics problem in a robot.

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