# A simulation platform design and kinematics analysis of MRL-HSL humanoid robot

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**Abstract.** This paper introduces MRL-HSL multibody simulation for the humanoid robot based on Matlab/ Simulink and Simscape software, which can be used for designing control systems, enhancing the stability of the robot and etc. purpose. MRL-HSL real-time simulation is a virtual humanoid robot which is the safe way of educational and research purpose without damaging to the robot in the real environment and reducing the cost of implementation. The structure of the robot includes a rigid multibody of the robot, actuators, sensors and it can be developed simply for other types of robots. For the gaiting purpose and other movement control designing aims, the forward kinematics is solved by Denavit Hartenberg (D-H) method and the analytical solution is used for solving the inverse kinematics. The kinematics chain consists of the head, Legs and arms of the humanoid robot. The cad models of each part of the virtual humanoid robot designed by SolidWorks software.

**Keywords:** Humanoid robot, Simulation, Rigid multibody, Kinematics.

## 1 Introduction

The MRL-HSL project was started in 2003 in the Mechatronics Research Laboratory in Islamic Azad University, Qazvin branch looking onward to enhance the knowledge of robotics and the MRL Humanoid Soccer League is aimed to develop a humanoid platform for research and education. MRL-HSL research center has the honor to hold the RoboCup from 2003 to 2018 [1].

The primary analysis before implementation in a real robot is needed to eliminate errors and reduce the costs. These analyses can lead to reducing damages and the process of time. The main purpose of this paper is a simulation for analysis forward and inverse kinematics of the MRL-HSL humanoid robot. This simulation includes several parts such as motors, sensors, controllers, physical modelling of the real robot architecture, robot body and joints which design in the Matlab/ Simulink software. Humanoid robot platform simulation based on Matlab is a simple and reliable approach which is low cost and easy to operate. Also, according to the flexibility of

Matlab, users can change the environment parameters, degrees of freedom and study about the humanoid robot on various condition. It should be noted that it can be used for solving a variety of kinematics problems [2, 3]. Matlab has a growing number of tools for dynamics simulation, especially dynamic solver libraries. Ideally, the model and simulation should be a trustable representation of the real system, so the result between simulation and the real robot should be little or no difference. Some researchers proposes a humanoid robot framework with different simulator such as VERP [4] and OpenHRP [5]. In the matter of humanoid robots kinematics problems, Kofinas et al. present an analytical forward and inverse kinematics solution for NAO standard humanoid robot platform [6]. In the other hand, Williams solved the kinematics problem for Darwin-OP humanoid robot [7]. Import from cad model is one of the most important things for robot simulation. The overall popularity of Matlab in universities is another reason for this purpose. Also, it is making it even easier to develop controllers and estimators based on blocks of Simscape and Simulink. Simscape provides a multibody simulation and it is one of the needs of mechanical and control engineers. While it is possible to work easily with solids, joints, constraints and etc. in this simulator. A comparison of the simulator with other simulators is listed in Table 1.

**Table 1.** A comparison of the simulator with other simulators

| **Simulator** | **Physic engine** | **Import CAD** | **ROS Interface** | **Open source** |
|---|---|---|---|---|
| MRL-HSL | Simscape multibody physic engine | Yes | Yes | Yes |
| Gazebo | ODE, Bullet, Simbody, DART | No | Yes | Yes |
| Vrep | ODE, Bullet, Vortex Dynamics, Newton Dynamics | No | Yes | No |
| Webot | ODE | No | No | Yes |

This paper presents a kinematic and dynamic simulator for MRL-HSL humanoid robot based on Matlab/Simulink, Simscape and SolidWorks, which can be expanded for many algorithms such as walking, kicking and other purposes. By this, physically more realistically motion simulation of the humanoid robot can potentially be achieved than with another common approach like Gazebo. This can be beneficial for the development of versatile humanoid robot motions and related controllers. The source code of the MRL-HSL humanoid robot simulation can find in [8] which is an open-source project. The simulation has been validated with a real humanoid robot.

This paper is organized as follows: section two, introduce the structure of MRL-HSL humanoid robot which including link parameters and diagram of the present simulation. Section three is about analysis of forward and inverse kinematics of the arm, leg and head. Section four discusses the results of solving the kinematics which is validated with real robot actions.

## 2 Structure of MRL-HSL humanoid robot

MRL-HSL real humanoid robot with 20 degrees of freedom (DOF) is equipped with Robotis Dynamixel MX series actuators which use two Dynamixel MX-28 in neck and head, six Dynamixel MX-106 for each leg and three Dynamixel MX-64 for each arm [9]. The overall structure of the robot has 83 cm in height and 6.6 kg weight (Fig.1.b) [10]. For the graphical purpose of simulation in a virtual environment, all of the components of the robot is designed by SolidWorks software with all details such as materials, inertias and weight of each part. Simulation of the humanoid robot is based on weight, inertia, canter of mass and graphical form of each component designed in the robot. For this reason, all of the part designed by SolidWorks has been moved to the Simulink software. The robot's overall shape in the Matlab needs assembling of each design components, so, for each part of the robot, a coordinate is defined and the robot assembly is based on these coordinates. Also, an end-effector coordinate is defined for kinematics purpose (Fig.1.a). Special thanks to [11], the robot simulation takes advantages of Dynamixel actuators in each joint, sub-controller (CM730) for using acceleration and gyroscope sensor, and force sensor which is located in the feet of the robots. The ID's number of each joint is like the Darwin-OP humanoid robot [12].

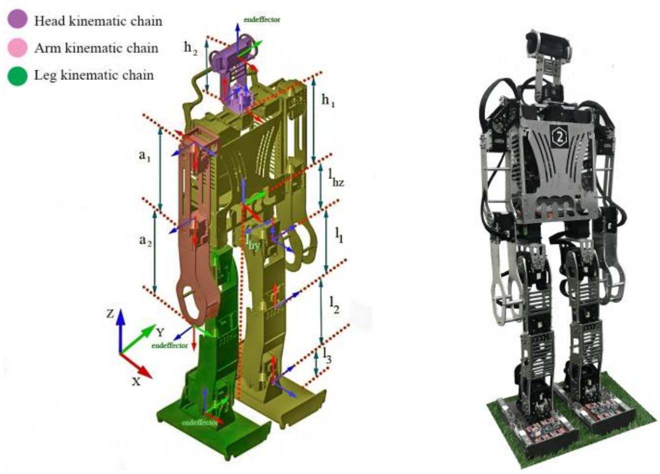


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**Fig.1.** MRL-HSL simulation humanoid robot and real humanoid robot

In Simulink model, the links coupled with one rotational degree of freedom and Simulink blocks have a definite physical meaning which is connected with other blocks by a signal line. MRL-HSL simulation humanoid robot has several chains consist of arms, legs, head and chest that they connected with each other and formed as an integral robot. Each chain defines as D-H parameters which express a transformation matrices. These transformation matrices that obtained from forward kinematics are in need because of solving inverse kinematics. The inverse kinematics gives joint angles, but since the Dynamixel actuator is used in the robot, a Dynamixel convertor block applies which generates desire angles for the actuator. In sums with the actual angle from the encoder of the actuator, and the error goes to the actuator controller. The controller command to the actuator and all process will be visualized in Matlab (Fig. 2).

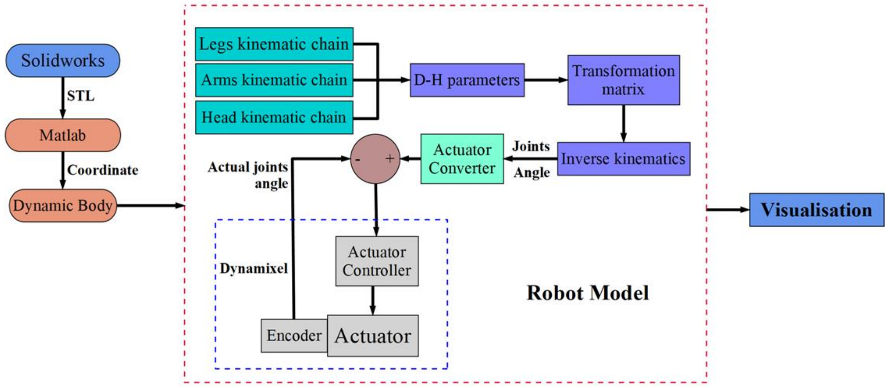


**Fig. 2.** Block diagram of the MRL-HSL simulation

Parameters of each part in Simulink is summarized in Table 2. In order to ensure accuracy solve, the simulation uses the ODE45 solver.

**Table 2.** Parameters of MRL-HSL components

| Name | Mass (gr) | Moment of inertia Ixx, Iyy, Izz (gr.mm2) |
|---|---|---|
| Chest | 2463 | 8720549.93, 32362766.04, 26505212.60 |
| Head | 143 | 191341.94, 1210405.71, 1287647.88 |
| Neck | 90 | 18191.09, 30322.49, 32570.55 |
| Shoulder | 2*39 | 57374.20, 47657.93, 45699.19 |
| Upper Arm | 2*247 | 98271.05, 906892.53, 919829.92 |
| Forearm | 2*248 | 925401.76, 965800.16, 1786134.92 |
| Hip yaw | 2*41 | 110180.71, 39820.58, 79877.42 |
| Hip roll | 2*358 | 416458.33, 552856.47, 235849.38 |
| Thigh | 2*263 | 154313.17, 5842352.97, 5810373.89 |
| Tibia | 2*129 | 127893.53, 1027984.81, 989075.93 |
| Ankle | 2*360 | 426375.54, 237912.72 , 565177.63 |
| Foot | 2*267 | 1246236.11, 1307545.02, 617163.22 |
| **Total Mass** | **6600** | |

## 3 Kinematics Analysis

A multi-body system consists of links which connected in a chain by revolute or prismatic joints and respectively create rotational or translational movement. With attaching coordinates to each joint, the circumstance for kinematics analysis is provided. Kinematics contains two portions, inverse and forward, which each of them is considered for a different purpose. Forward kinematics is a way for mapping from joint space to Cartesian space [13, 14]. The forward kinematics equation is written as:

$$x = f(\theta) \tag{1}$$

Where, the outputs of the equation (1) illustrate the position and orientation of the end effector respect to the reference frame that described by homogeneous transformation matrices. So transformation matrices describe cartesian space. Also, the inputs of the equation are joint angles. There are two different way of solving forward kinematics. In this paper, a modified D-H method is used for this purpose. On the other hand, inverse kinematics calculate joint angles with considering the position and orientation of end effector relative to the base frame. It means that the cartesian space mapping to joint space by equation (2).

$$\theta = f^{-1}(x) \tag{2}$$

Obtaining angles from equation (2) is not unique and multiple solutions exist. In the case of multiple solutions, there are two possible way, closed form and numerical solution. a closed-form solution is much faster than the numerical solution [15]. For this reason, the closed form solution is used in this article. In this paper forward and inverse kinematics problems are solved for arm, leg and head of the MRL-HSL humanoid robot. As shown in Fig.1.a there are five kinematics chains in humanoid robot and the reference frame of each chain located at the chest. With regard to the hardware design of the robot, human limits factor and rules of the RoboCup humanoid robot [16], all of the joint angles are limited in specific angles. These limitations are listed in the D-H table in each section.

### 3.1 Arm Kinematics

The MRL-HSL robot arm includes shoulder joint, upper arm, elbow joint, lower arm and end-effector. The arm has 3 DOF, two DOF located at the shoulder, the elbow has one DOF. The structure of the left arm is shown in Fig.1.a. The parameters of D-H are listed in Table 3. Which $traX$ means Translation of X-axis and $rotX$ means Rotation around X-axis and respectively Y and Z means Axis of them. According to D-H convention, the construction of the forward kinematics describes in equation (1).

**Table 3.** Three-DOF arm D-H parameters

| i | $\alpha_{i-1}$ (deg) | $a_{i-1}$ (mm) | $\theta_i$ (deg) | $d_i$ (mm) | Variable range ($\theta_{min}$, $\theta_{max}$) |
|---|---|---|---|---|---|
| 1 | | | $rotX(-90).rotZ(90)$ | | |
| 2 | 0 | 0 | $\theta_2$ | 0 | (-90, 180) [17] |
| 3 | 90 | 0 | $\theta_4$ | 0 | (0, 140) [18] |
| 4 | 90 | $a_1$ | $\theta_6$ | 0 | (0, 145) [17] |
| 5 | | | $traX(a_2)$ | | |

$$T_{end}^{base} = \begin{bmatrix} c_2 s_6 - c_4 c_6 s_2 & c_2 c_6 - c_4 s_2 s_6 & -s_2 s_4 & p_x = a_2(c_2 s_6 - c_4 c_6 s_2) - a_1(c_4 s_2) \\ c_6 s_4 & -s_4 s_6 & -c_4 & p_y = s_4(a_1 + a_2 c_6) \\ -s_2 s_6 - c_2 c_4 c_6 & c_2 c_4 s_6 - c_6 s_2 & -c_2 s_4 & p_z = -a_2(c_2 s_6 + c_2 c_4 c_6) - a_1(c_2 c_4) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Where $s_i = \sin(\theta_i)$ and $c_i = \cos(\theta_i)$. To solve the inverse kinematics problem for obtaining the arm joints angles, kinematics problem decomposed into geometric and algebraic solution. Hence, because of the arm structure, to determine the elbow joint angle, the geometric method is used. Fig. 3.a demonstrate hand structure of the robot which is used for solving of hand inverse kinematics. On the other hand to calculate shoulder joint angles $\theta_2$ and $\theta_4$, the algebraic method is used. There are two solution for $\theta_2$ and $\theta_6$. It should be noted that this kinematics written for the left hand, the right hand kinematics is similar to the left one.

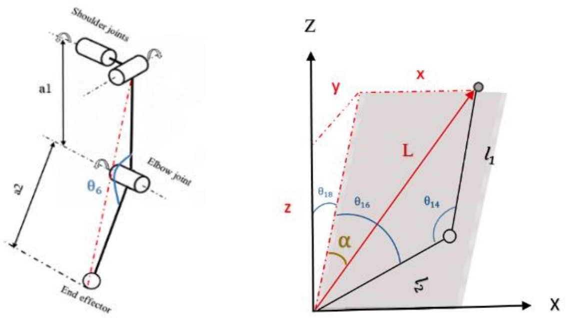


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**Fig. 3.** a) Hand kinematics of the robot b) Leg kinematics of the robot

$$A = \frac{a_2^2 + a_1^2 - p_x^2 - p_y^2 - p_z^2}{2a_2 a_1}$$

$$\theta_6 = 90 - \cos^{-1}(A) \quad \text{or} \quad -\cos^{-1}(A)$$

$$\theta_4 = \sin^{-1}\left(\frac{p_y}{a_1 + a_2 * c_6}\right) \quad (4)$$

$$B = -a_2 s_6, \quad C = -a_1 c_4 - a_2 c_4 c_6$$

$$\theta_2 = 2\tan^{-1}\left(\frac{C + \sqrt{B^2 + C^2 - p_x^2}}{B + p_x}\right) \quad \text{or} \quad 2\tan^{-1}\left(\frac{C + \sqrt{B^2 - C^2 - p_x^2}}{B + p_x}\right)$$

## 3.2 Leg Kinematics

Parameters of the leg serial chain in the D-H table listed as Table 4. The reference frame of this chain is located at the chest of the robot and the chain end effector is sitting at the bottom of the sole.

**Table 4.** Six-DOF leg D-H parameters

| i | $\alpha_{i-1}$ (deg) | $a_{i-1}$ (mm) | $\theta_i$ (deg) | $d_i$ (mm) | Variable range ($\theta_{min}$, $\theta_{max}$) |
|---|---|---|---|---|---|
| 1 | | | $traY(l_{hy}).traZ(l_{hz})$ | | |
| 2 | 0 | 0 | $90+\theta_8$ | 0 | (-45, 45) |
| 3 | 90 | 0 | $90+\theta_{10}$ | 0 | (0, 40) [19] |
| 4 | 90 | 0 | $\theta_{12}$ | 0 | (-45, 90) |
| 5 | 0 | $-l_1$ | $\theta_{14}$ | 0 | (0, 120) [20] |
| 6 | 0 | $-l_2$ | $\theta_{16}$ | 0 | (-90, 90) |
| 7 | -90 | 0 | $\theta_{18}$ | 0 | (-45, 45) |
| 8 | | | $rotZ(90).rotY(-90).traZ(-l_3)$ | | |

Base on the D-H method with given $\theta_8$ to $\theta_{18}$, the very large matrix generated that the forward kinematics calculate it. Solving inverse kinematics for calculate the leg joints angles, kinematics problem decomposed into a geometric and algebraic solution. $L$ is the distance between the ankle and the hip. As shown in Fig. 3.b, with considering triangular $Ll_1l_2$ the angle of the knee is calculated. Also Fig. 3.b shows the ankle roll and ankle pitch angles. By displacement, the transformation matrices with those elements that is calculated previously, hip yaw, roll and pitch angles will be attain in equation (5) [21].

$$L = x^2 + y^2 + z^2$$

$$\theta_{14} = \cos^{-1}\left(\frac{L-l_1^2-l_2^2}{2l_1l_2}\right), \quad \theta_{16} = atan2(y,z), \quad \theta_{18} = \sin^{-1}\left(\frac{x}{\sqrt{L}}\right) - \sin^{-1}\left(\frac{l_1 \sin\theta_{14}}{\sqrt{L}}\right)$$

$$\mathrm{T} = T_{base}^{end}.rotX(\theta_{18}).rotY(-\theta_{16}-\theta_{14}) = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$\theta_8 = atan2(-r_{12}, r_{22}), \quad \theta_{10} = asin(r_{32}), \quad \theta_{12} = atan2(-r_{31}, r_{33})$$

### 3.3 Head Kinematics

According to the D-H table, parameters of the head serial chain are defined as Table 5. As mentioned earlier the reference frame of the head chain located at chest. As the robot needs to track the object, in the field of humanoid soccer robot the object is ball, the end effector coordinate is set at the camera.

**Table 5.** Two-DOF head DH parameters

| i | $\alpha_{i-1}$ (deg) | $a_{i-1}$ (mm) | $\theta_i$ (deg) | $d_i$ (mm) | Variable range ($\theta_{min}$, $\theta_{max}$) |
|---|---|---|---|---|---|
| 1 | | | $traZ(h_1)$ | | |
| 2 | 0 | 0 | $\theta_{19}$ | 0 | (-90, 90) |
| 3 | -90 | 0 | $\theta_{20}$ | 0 | (-30, 90) |
| 4 | 90 | 0 | 0 | $h_2$ | |

Base on the D-H method with given $\theta_{19}$ and $\theta_{20}$, the forward kinematics calculate the homogeneous transformation matrices which yield the following homogeneous matrices. Based on these parameter, according to the D-H rules, constructed the matrices, witch multiplied together, yield the following homogeneous.

$$T_{end}^{base}=\begin{bmatrix} c_{19}+c_{20} & -(s_{19}+s_{20}) & 0 & p_x=90(\cos(\theta_{19}+\theta_{20})-\cos\theta_{19}) \\ s_{19}+s_{20} & c_{19}+c_{20} & 0 & p_y=90(\sin(\theta_{19}+\theta_{20})-\sin\theta_{19}) \\ 0 & 0 & 1 & p_z=h_2+h_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

The inverse kinematics of the head is solved base on algebraic solution as shown in equation (7). With given desired position in the space, the result of the inverse kinematics is joint angles of the head.

$$\begin{gathered}\theta_{19}=atan2(p_y,p_x) \quad \text{or} \quad atan2(-p_y,-p_z) \\ \theta_{20}=acos\left(\frac{p_z-h_1}{h_2}\right) \quad \text{or} \quad -acos\left(\frac{p_z-h_1}{h_2}\right)\end{gathered} \quad (7)$$

## 4 Results and Conclusion

The MRL-HSL humanoid robot simulation in this paper was validated with a real robot. In order to validate the simulation, a kinematics algorithm is calculated. By giving different angles in joint space the position and orientation of the body are located at the same place in the space. In the other hand, the cartesian space was mapping to joint space by inverse kinematics as well as a real robot. The outputs of inverse kinematics have shown in Fig. 5 which is the output of the posture of the humanoid robot in Fig. 4. The red lines show the angle of each actuator which is read by the encoder in simulation and dot line show the outputs of the encoder of each joint of the actual robot. The results have shown that the behavior of the simulated robot is resembling the real robot. So this simulation can be used for controlling purposes and another aspect of the humanoid robots algorithm such as walking and kicking.

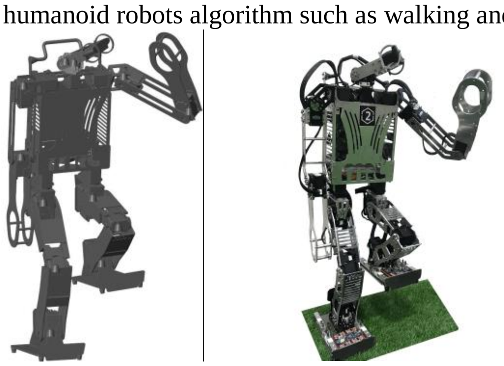

**Fig. 4.** The posture of the humanoid robot in simulated and real robot

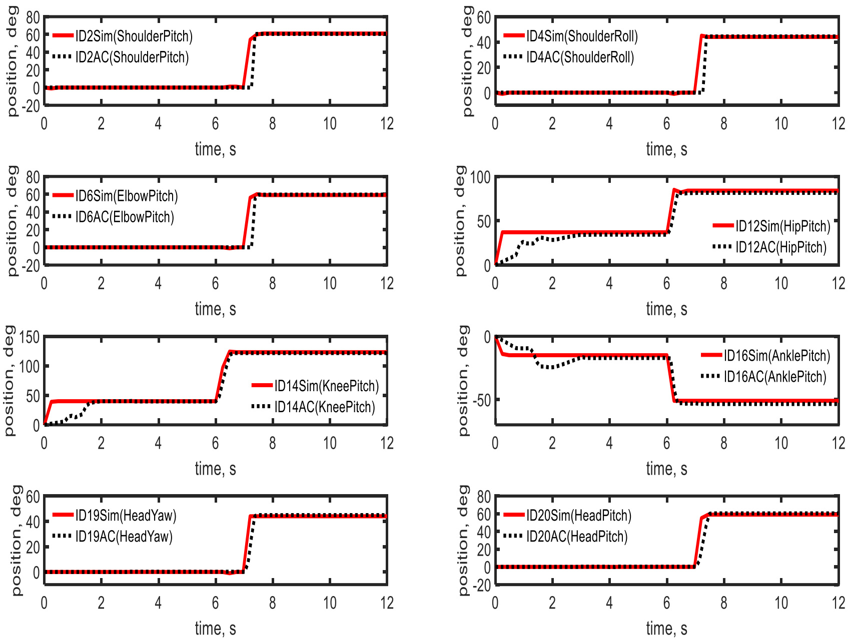


**Fig. 5.** Outputs of inverse kinematics simulated and real humanoid robot in different actuators

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