A Frontal Plane Waist Motion With A Limit HipOffset Y Length Using Inverse Kinematics In NAO Humanoid Robot To Align The Center of Mass (COM) And Robot’s Foot

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Abstract. All articles The design of humanoid robot walking motion is achievable only through the use of robot kinematics. In this paper, we study the problem of waist motion (HipOffsetY) in frontal plane for NAO humanoid robot as a starter to make the robot walk. The inverse kinematics allow NAO humanoid robot to record the robot configuration ways to go from the three-dimensional space of the robot to the joint space. The inverse kinematics defined the relation between points in the three-dimensional space (position and orientation) and joint values in the joint space of the robot’s kinematics chain. The simulation using Robotic Simulator Simulation V-REP (Virtual Experimentation Platform) by Coppelia Robotics. Inverse Kinematics can provide the mechanism to transform such a trajectory into another trajectory in the joint space of the robot. The inverse kinematics is demonstrated in waist motion to the left and right at 0.05m.

1. Introduction
Articulated robots with multiple degrees of freedom, such as humanoid robots, have become popular research platforms in robotic. Our work focuses on autonomous humanoid platforms using right hip roll joint (RHipRoll) and left hip roll joint (LHipRoll) capable of performing waist motion with a limit HipOffSet Y length using inverse kinematics in NAO humanoid robot. The design of complicated motions is achievable when using robot kinematics, which is an application of random robotics chain. The importance of solving the inverse kinematics problem for NAO lies in the ability to follow any (predefined or dynamically-generated) trajectory in the three-dimensional-space with the two robot’s legs. The inverse kinematics can provide the mechanism to transform such a trajectory into another trajectory in the joint space of the robot.

The inverse kinematics problem is to define ways to go from the three-dimensional space of the robot joint space [1]. The strategy to calculate the hip joint can be split into two classes, closed-form solutions and numerical solutions. In this research, we are not interested in numerical approach as it is generally much slower than the corresponding closed-form solution. We will focus our research to closed-form solution methods. Closed-form means a solution method based on analytic expressions or on the solution of polynomial of degree 4 or less [2]. The closed-form method can divide into two methods of obtaining the solution, algebraic and geometric. In a geometric approach, the spatial geometry of the hip join will be decompose into several-geometry problems.

2. Background
The inverse kinematics presented here solve the problem for the two joints (right hip roll and left hip roll) of the robot based on the research by [3]. Our work focuses on autonomous humanoid platforms.
with multiple manipulators capable of performing waist motion (HipOffsetY) at frontal plane. This motion is required in carry forward our research in humanoid robot walking in stable condition. In humanoid robot research the environment of robot locomotion is the basic field that can be explore further. In a study about humanoid robot walking thesis [4], the author classified the robotics cultural society into three types, namely industrial robotics, service robotics and personal robot. This remark has been supported by [5] as they defined that a qualify as a robot, a machine has to be able to do two things which are obtain information from its surrounding and perform something physical, such as move or manipulate objects.

The most extensively robots today are the industrial robots. The development of the computer field has led to the rapid growth of industrial robotics. It contributed by the automotive industry in majority. A manipulator will be considered solvable if the joint variables can be determined by an algorithm that allows one to determine all the sets of joint variables associated with a given position and orientation [2]. The main point of this definition is that we require, in the case of multiple solutions, that it be possible to calculate all solutions. In this research, to solve kinematic equations, we will consider geometric solution for the right hip roll and left hip roll.

Humanoid robots are very useful to human being because they play a big part as the basis and contribute to the prosperity that poured around the world but they are not intelligent enough. Due to the technological advances in the robotics study, a new class of robotics emerged into this world which called as service robots. According to [6], the author clarified that the service robotics for companies and individuals will be on the increase in the next few years. Currently, this technology is dominated by the wheeled robots. However, some bigger Japanese companies have been working on numbers of humanoid robot projects to make the service robots idea become a reality.

The service robots are not designed to produce goods, but it provides hospitality and comfort to the human being at home. Each type of robot that mentioned earlier was created for a common course which is to facilitate human in passing through their everyday life. In humanoid research environment, robotics, artificial intelligence, cybernetics, biomechatronics, sport medicine, and rehabilitation are the field that can be explore further [7]. However, in humanoid robot walking environment, examples of constraint in this field are walking, jumping, running, standing and crawling. In order to solve the humanoid robot walking, the algorithm should be formulated in a system as shown in Figure 1 [2].

![Figure 1. High level of block diagram of a robot control system](image)

The humanoid robot walking design starts from its motion requirements, so the dimensions, joint range motion, joint velocities and forces should be studied. After that, the link design could properly start. Humanoid robot deals with the study of walking, so the human walking will be analyzed. First, human biomechanics anthropometry is studied. Next, the human walking motion is analyzed. Various terms are used to describe the three perpendicular intersecting planes in which many, although not all, joint movements occur. The common point of intersection of these three planes is most suitably defined as the centre of mass of the whole human body. The planes are known as cardinal planes — the sagittal, frontal and transverse (horizontal) planes as shown in Error! Reference source not found..
The number refers to the Error! Reference source not found. where the three planes are illustrated. The humanoid robot walking is realized on the three (3) planes. Based on the study done by [9], the plane parallel to the xz-plane is called as sagittal plane. Next, the plane parallel to the yz-plane is called the frontal plane. Then, the plane parallel to the xy-plane is called as the horizontal (transverse) plane.

3. Kinematics
Kinematics is not concerned with the internal forces and external forces that cause the movement, but, rather with the details of the movement itself. A complete and accurate quantitative description of the simplest movement requires huge volume of data and a large number of calculations, resulting in an enormous number of graphic plots. For example, describing the movement of the lower limb in the sagittal plane during one stride can require up to 50 variables. These include linear and angular displacements, velocities and accelerations.

It should be understood that any given analysis may use only a small fraction of the available kinematic variables. Another example is an assessment of a running broad jump may require only the velocity and height of the body’s center of gravity (COG). In order to keep track of all the kinematics performance matrices, it is important to establish a convention system. Thus, a spatial reference system must be established to analyze the movement relative to the ground or the direction of gravity.

The study done by [6] explained that walk is the alternating repetition, from one leg to another, of the same fundamental. Research done by [10] defined that one step of bi-pedal locomotion as the period in which motion is repeated again and again as shown in Figure 3.

4. The Aldebaran NAO Humanoid Robot Specification
5. Solving the Inverse Kinematics Problem

Absolute control of manipulators and effectors can be successful by solving the inverse kinematics problem, where the values of $\theta_i$ of the angles of numerous joints must be defined to place the manipulator to a specific target position (translation or orientation). The analytical solutions are fast and exact, but to define them takes significant effort.

5.1 Denavit-Hartenberg Convention

To make the transformation between two frames adjacent to a joint, we will use Denavit-Hartenberg (DH) parameters ($a$, $\alpha$, $d$ and $\theta$) to compose the frames. For the NAO, these parameters are provided by the manufacturer. The current angle (state) of the joint is $\theta$. Given the parameters of some joint $j$, the DH parameters matrix that describe the translation and orientation of the reference frames of joint $j$ with respect to the reference frame of the previous joint $j-1$ is

$$T_{j-1}^j = R_x(a_j)A\left(\begin{bmatrix} a_j & 0 & 0 \end{bmatrix}^T\right)R_x(\theta_j)A\left(\begin{bmatrix} 0 & 0 & d_j \end{bmatrix}^T\right)$$

(1)

Where:

- $a_j$ = the distance from $Z_i$ to $Z_{i+1}$ measured along $X_i$
- $\alpha_j$ = the angle from $Z_i$ to $Z_{i+1}$ measured about $X_i$
- $d_j$ = the distance from $X_{i-1}$ to $X_i$ measured along $Z_i$
- $\theta_j$ = the angle from $X_{i-1}$ to $X_i$ measured along $Z_i$

This matrix is a product of invertible matrices. So, a DH transformation is always invertible.

| Frame        | $a$        | $\alpha$ | $d$ | $\theta$     |
|--------------|------------|----------|-----|---------------|
| Base         |            |          |     |               |
| LHipYawPitch | 0          | $\frac{-3\pi}{4}$ | 0   | $\theta_1 - \frac{\pi}{2}$ |

Table 1. DH parameters for left leg of the NAO robot
5.2 Inverse Kinematics Methodology

5.2.1 Construct the Numeric Transformation. With a desired target position, defined by an orientation vector $\vec{a} = [a_x, a_y, a_z]^T$ and translation vector $\vec{p} = [p_x, p_y, p_z]^T$, it becomes simple to reconstruct the target transformation matrix:

$$T = A(\vec{p})R_x(a_z)R_y(a_y)R_x(a_x)$$  \hspace{1cm} (2)

First, the numeric transformation for the left leg needs to be constructed using equation (2) by substituting the value from Table 1.

$$\hat{T} = (A_{Base}^0)^{-1}T(A_{End}^6)^{-1}$$  \hspace{1cm} (3)

After substituting the value, using equation (3), a chain from the base frame of the joint to the rotated frame of the last joint. The LHIpYawPitch, $\theta_1$, is constructed by rotating by $-\frac{3\pi}{4}$ about the x-axis with respect to the torso frame. The origin aligned need to rotate by $\frac{\pi}{4}$ about the x-axis to make the first joint aligned with the z-axis.

$$\hat{T} = R_x(\frac{\pi}{4}) \hat{T}$$  \hspace{1cm} (4)

From equation (4), we can determine that the first four joints LHIpYawPitch($\theta_1$), LHIpRoll($\theta_2$), LHIpPitch($\theta_3$), LKneePitch($\theta_4$) affect the position and orientation of the end effector and other two joints (LAnklePitch($\theta_5$), LAnkleRoll($\theta_6$)) affect its orientation. Since we operate in the three-dimensional space, it is suitable if only three joints are affecting the position of the end effector.

After LAnkleRoll($\theta_6$) is now known, the two rotations at the end of the chain along with transformation $T_5^6$, we can determine as below transformation:

$$\hat{T}' = \hat{T}'(T_5^6R_x(\pi)R_y(-\frac{\pi}{2}))^{-1}$$  \hspace{1cm} (5)

After LKneePitch($\theta_4$) and LAnklePitch($\theta_5$) are known from the Table XXX, the two transformations $T_3^4$ and $T_4^5$ can determine by below equation:

$$T' = \hat{T}'(T_3^4T_4^5)^{-1}$$  \hspace{1cm} (6)
In equation (6), the translation block in will be zero because only three hip joints left which affect the orientation.

\[
\hat{\theta}_2 = \cos^{-1}(T_{(2,3)}')
\]

\[
\theta_2 = \hat{\theta}_2 - \frac{\theta}{4}
\]

Where, \(\hat{\theta}_2\) is the DH parameter \(\theta\) for the second (LHipRoll) joint.

6. Result and Discussion

6.1 Inverse Kinematics For Hip Roll Joint

Left leg has six joints (LHipYawPitch, LHipRoll, LHipPitch, LKneePitch, LAnklePitch and LAnkleRoll) make a kinematic chain of the robot. We will only consider left hip roll (LHipRoll) and move the robot center of mass (COM) aligned with the robot’s foot (support polygon) with 0.05m length at HipOffset Y.

The robot is usually equipped with a lot of embedded sensors to the CPU. A Force Sensitive Resistor (FSR) is used to detect the contact of the feet with the ground. There are four (4) Force Sensitive Resistor (FSR) placed below of each foot that measures the resistance change in corresponding with the applied pressure. In this research FSRs from left leg (LFsrFL, LFsrFR, LFsrRL, LFsrRR) are considered to analyse. All the FSR are analyzed using X-axis force and Y-axis force according to the NAO humanoid robot documentation. The robot waist will move to the right and left in 0.05 m to make sure the robot torso center of mass (COM) is aligned with the foot.
According to Figure 6, the maximum force for left foot front left FSR (LFsrFL) showed in the figure is 0.088035 N and -0.09972 N at minimum in X-axis force. This showed that when the waist of the robot moved 0.05m to the left through HipOffsetY dimension, the force at the foot of the robot is maximum as the robot torso or center of mass (COM) is aligned with the foot. During t=21s the force activated at that time is 0.0143 N. This showed that the LFsrFL is activated at that time as the robot torso or center of mass (COM) is moving to align with the foot.

At Y-axis, the maximum force for LFsrFL is -0.25378 N according Figure 6. This showed that when the robot waist moved to the left at 0.05m with HipOffsetY dimension, the force vector activated at t=9s until t=20s is 0.25378 N at the negative side of Y-axis. This also explained that the robot torso or center of mass (COM) is aligned with robot foot during this time. During t=21s until t=30s, the force activated at the LFsrFL is -0.23662 N as the robot waist started to move 0.05 m to the left which is HipOffsetY dimension and make the robot torso is aligned with the foot.

According to Figure 7, the maximum force for left foot front right FSR (LFsrFR) produced is 0.000471 N and 0.000444 N of minimum at X-axis. This showed that the robot torso or center of mass (COM) is aligned with the robot foot when the robot waist moved to the left at 0.05m. At t=20s until t=21s, the robot torso or center of mass (COM) produced a small vibration while moving the waist to the left at 0.05m with HipOffsetY dimension. The vibration is produced because of the gravity that
pulled the robot body to the ground. That is why the result showed that, the LFsrFR value increased from 0.000444 N to 0.00471N X-axis.

At the Y-axis, the maximum force for LFsrFR is 0.004166 N according Figure 7. This showed that when the robot moved to the left 0.05m with HipOffsetY dimension, the force vector activated starting during t=21s at Y-axis.

According to Figure 8, the maximum force for left foot rear left (LFsrRL) produced is -0.1209 N and -0.02787 N at minimum. This showed that the robot torso or center of mass (COM) is aligned with the foot of the robot when the robot waist with HipOffsetY dimension moved to the left at 0.05m. At t=20s until t=30s, the force produced at LFsrRL is -0.1209 N at the positive side of X-axis. This explained that, the robot is moving its waist to the left with HipOffsetY dimension to make the robot torso is aligned with the foot.

At the Y-axis, the maximum force that produced at t=21s -0.2051 N and -0.20334 N at minimum in Figure 8. This showed that the robot LFsrRL produced 0.2051 N at the negative side of the Y-axis. During this time, the robot waist is moved to the left at 0.05m with HipOffsetY dimension and the robot torso is aligned with the foot. From t=21s until t=30s, the force vector produced at LFsrFL is -0.2051 N at Y-axis. This explained that the robot waist is moving to the left to make its torso aligned with the robot foot.
According to Figure 9, the maximum force produced at left foot rear right FSR (LFsrRR) is 0.000471 N and 0.000436 N in minimum at the positive side of X-axis. This showed that the robot waist is moved to the left at 0.05m and aligned with robot foot. From t=21s until t=30s, the LFsrRR is produced force vector of 0.00471 N at the positive side of the X-axis. This showed that the robot waist is moving to the left side at 0.05m during this period of time.

At the Y-axis, the maximum force produced at LFsrRR of the robot is 0.0042 N and 0.003109 N at minimum force. During this time, the robot waist is moved to the left and the aligned with the foot of the robot. At t=21s until t=30s, the force vector produced is 0.0042 N at positive side of Y-axis. This showed that, the robot waist is moving the left side to make it aligned with the foot.

7 Conclusion
This paper used a simulator from Robotic Simulator Simulation V-REP Virtual Experimentation Platform Coppelia Robotics. The Aldebaran NAO humanoid robot is used to simulate our work. Since the humanoid robots are expensive to have, using simulator is necessary and convenient to make this research in proper way. Our approach in forward kinematics is based on the standard principled methods to study about robot kinematic chains. Also, this paper approach to NAO kinematics is based on the standard principle methods for studying robot kinematics chains.

Based on the result and discussion, the force vector showed in Figure 6, Figure 7, Figure 8, and Figure 9 they are in maximum value when the robot waist is moved to the left at 0.05m with HipOffsetY dimension and made its COM aligned with the robot foot. This explained that, to make the robot walk in stable condition, the frontal plane motion of the robot must be 0.05m at the maximum length. The LFsrFL, LFsrFR, LFsrRL, and LFsrRR produced force vectors based on the robot torso is aligned with the robot foot to make it stable.

Since the robot kinematics is the base for most application related to robot motion, this research expected that it will be useful not only is frontal plane motion, but also to any humanoid robot walking kinematics research. This research believe that the NAO developers can take advantage of this paper to work on omni-directional walk algorithms, dynamic balancing methods, forward kinematics robot walking, etc.

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