New Approach to the Modeling of a Humanoid Robot: Applied to Robot RH-ARP

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ABSTRACT: *The work presented in this article is interested in a modeling of a humanoid robot. A new approach based on the synthesis of previous work and the analysis of human walking is proposed. The prototype is a humanoid robot designed to 18 DOF divided by six DOF in the arm, five DOF in the foot and a height of 172 cm of a humanoid. The modeling approach chosen is the Denavit Hartenberg, we considered the kinematic chain as a simple joint chain .In this paper, we will present the mechanical construction, direct geometric modeling, inverse geometric modeling and animation in building an upper humanoid robot in virtual environment.*

Keywords: Humanoid Robot, Direct Geometric Modeling, Inverse Geometric Modeling, Virtual Reality Modeling Language

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1. Introduction

The realization of such system or robot requires first to establish its mathematical model. Modeling of humanoid robot was and remains to this day an ambiguous model; several studies have been made by several approaches and methods. Some studies have considered the joints of humanoid robot as an arborescent structure, other as simple open chain or closed.

Modeling methods are also different: the method of Denavit Hartenberg (DH), the concept of modeling (father-child) uses equation Rodrigues and the state space method. This work focuses on modeling the humanoid robot RH-ARP.

2. Modelling Humanoid Robot RH-ARP

2.1Chain kinematic

When we started to design the system, the first thing that we set it is the kinematic chain of the humanoid robot.

Articulated mechanical system (MAS) is a mechanism with a more or less similar to that of the human arm. It can replace or prolong its action.

The role of a manipulator is to bring the body in a terminal situation (position and orientation) given according to the characteristics of speed and acceleration data. Its architecture is a kinematic body, usually rigid (or assumed as such), joined by links called joints.

2.2 Structure of RH-ARP

Writers presented the average dimensions of the human body according to the height of the person [2]. We have used this information to properly size a model.We set the size of the prototype HR-ARP designed to 172 cm (figure 1).

3. Specification of HR-ARP

3.1 Degree of freedom

We set the number of degrees of freedom of our prototype HR–ARP at 18 DOF.

Three DOF in each arms divided by an angle of rotation of θ, at the shoulder elbow and wrist. Six DOFper leg divided by three at the hip (rotation through an angle θ rotation through an angle ψ and rotation through an angle φ), one at the knee (rotation through an angle φ) and two at the ankle (rotation through an angle θ et φ).See table below.

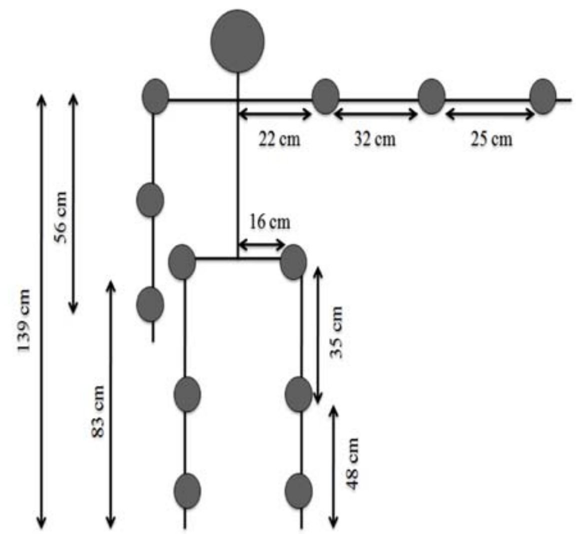

Figure 1. Length of segments of the robot expressed in relation to a height of the person equal to 172 cm

DOF	Head	
	arm 3 DOF/ arm (x2) Shoulder 1 (x2) elbow1 (x2) Wrist1 (x2)	6
	leg 6 DOF/leg (x2) hip 3 (x2) knee 1 (x2) ankle 2 (x2)	12
	Total	**18**

Table 1. Specifications of RH-ARP

3.2 The size of the HR-ARP

The size of the human robot designed is equal to 172 cm, Consistent with figure 1, we obtain a length of the arm equal to 32 cm, the forearm equal to 25 cm, a length equal to 42 cm for thigh and 43 cm for the leg. See table below:

3.3 Movable rang of each joint

Based on some pre-set configurations [3], we have set for our prototype , blocks represented in the following table.

Dimension	size	172	cm
	arm	32	cm
	forearm	25	cm
	thigh	42	cm
	leg	43	cm

Table 2. Size of each paw

	Joint	**Movable rang**
Arm	Shoulder	-180° à 60°
	elbow	-90° à 0°
	wrist	-70 à 90°
Leg	hip	-12° à 12°
		-80 ° à 80 °
		-15 ° à 15 °
	knee	0° à 180 °
	ankle	-12° à 12°
		-25° à 25°

Table 3. Movable rang of each joint

4. Different Modeling Approaches of Simple Open Chain

Modeling of robots in a systematic and automatic way requires an adequate method for the description of their morphology. Many notations have been proposed Denavit, Sheth, Renaud, Khalil [4]. Rodriguez's equation [5], [10].

The symbolic calculation of the geometric kinematic and dynamic by the computer has been a great deal of work. The most common is the Denavit Hartenberg, but this method developed for simple open structures, presents ambiguities when applied to robots with closed structures or arborescent. Therefore, we use the notation of Khalil & Kleifinger that allows the description homogeneous, and with a minimum number of parameters, open architectures simple and complex of mechanical articulation system.

4.1 Different approaches for connecting a humanoid robot

In this section, we took inspiration from articles [1, 2, 3, 4, 6, 7, 8, 9] for the development of our work.

4.2 Synthesis of previous work

The work done by "*Min-Chan Hwang* " [6] for geometric modeling and kinematics of a humanoid robot the authors considered each leg of the robot manipulator as an independent, and they calculated the geometric model and its kinematic model. For this we consider the humanoid robot as simple joint chain.

In the work done by "*J. de Lope*" [7], in the direct kinematics of the humanoid PINO robot as regards what the relative position and orientation of one foot from the other is solved easily considering a model as a robotic chain of links interconnected to one another by joints. The first link, the base coordinate frame, is the right foot of the robot. We assume it to be fixed to the ground for a given final position or movement, where the robot global coordinate frame will be placed. The last link is the left foot, which will be free to move.

In the work done by "*Muhammad.A*"[8], the authors set two bases coordinate frames B1 and B2 for the Hubo KHR-4 humanoid robot. B1 is established at the center of the neck and is the reference coordinate frame for the arms and the head, and B2 is the reference coordinate frame for the legs. B2 is linked to B1 through a waist joint, and there is a simple link transformation matrix between B1 and B2. As a result, B1 is considered to be the global base coordinate frame for the whole robot.

In the work done by "*M. ARBULU* " [3] & "*Carlos Balaguer* " [9],They divided the body of the humanoide robot RH-0 in two independent parties (half-humanoid) manipulators.and they considere each half-humanoid as a open joint chain.

5. Method of the Modeling of Robot Proposed RH-ARP

5.1 Modeling of the human being

In this section we will regard the human being as being a series of articulations and bonds called the articulated chains. The following figure illustrates this structure:

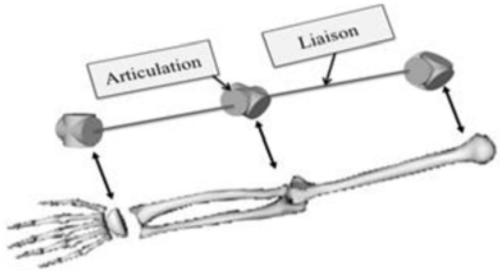

Figure 2. Chain articulations

For several years, many researchers have been undertaken with an aim of modeling the human being. Nowadays there exist several models, each one of them presents a projection in the modeling of the man. In what follows, a model of robot humanoid (arm, hand, leg, foot) will be proposed.

By the fact that the left hand and the right foot move simultaneously and inversely, on the basis which we want to have, the position and the orientation of the final body (right foot left hand left-foot right hand). We established the following model:

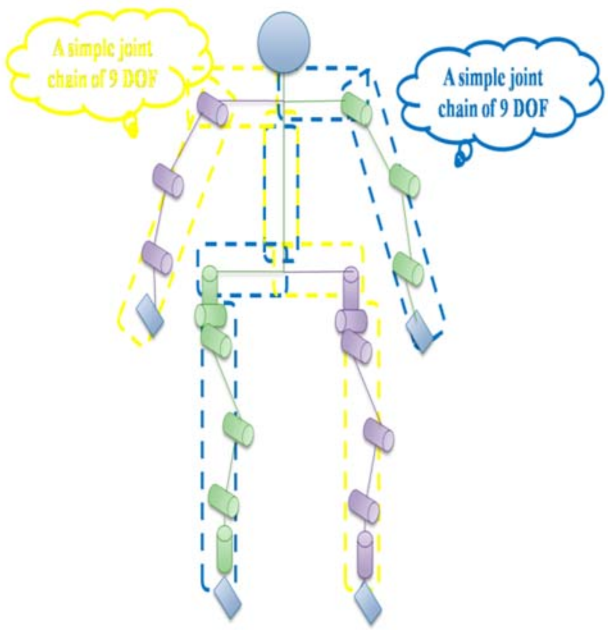

Figure 3. Model suggested for prototype RH-ARP

considering that the left hand and the right foot as only one articular chain and the right hand with left foot like a second simple articular chain.

5.2 Direct geometrical modeling of the RH-ARP

We use the notation of Denavit Hartenberg Modified to have the representation of our prototype and the matrix of transformation.

From the table and given the transition matrix of elementary Denavit-Hartenberg, we write the homogeneous transformation matrices T_i^{i-1}:

Matrix of DH:

$$T_3 = T_1^0 * T_2^1 * T_3^2$$

We put

$$C_i = \cos(\theta i)$$

$$S_i = \sin(\theta i)$$

Parameter \ Articulation	1	2	3	4	5	6	7	8	9
σ_i	0	0	0	0	0	0	0	0	0
α_{i-1}	$\pi/2$	0	0	0	$\pi/2$	$\pi/2$	0	0	$\pi/2$
a_{i-1}	0	a_1	a_2	0	0	0	a_7	a_8	0
Θ_i	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6	Θ_7	Θ_8	Θ_9
r_i	0	0	0	0	0	0	0	0	0

σ_i : Type of articulation, 0 if the joint is revolute and prismatic 1 if it is.
α_{i-1} : Angle between zi-1 and zi around xi-1.
I-1 : Distance between zi-1 and zi around xi-1.
Θ_i : Angle between xi-1 and xi zi around.
r_i : Distance between xi-1 and xi zi around.

Table 1. Paramètres de Denavit-Hartenberg du RH-ARP

Therefore

$$T_1^0 = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^1 = \begin{bmatrix} C_2 & -S_2 & 0 & a_2 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} C_3 & -S_3 & 0 & a_3 \\ S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

We have:

$$T_3^0 = \begin{bmatrix} C_{1+2+3} & -S_{1+2+3} & 0 & a_2 * C_1 + a_2 * C_{1+2} \\ 0 & 0 & -1 & 0 \\ S_{1+2+3} & C_{1+2+3} & 0 & a_2 S_1 + a_3 * S_{1+2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Knowing that:

$$C_\alpha = \cos(\alpha)$$

$$C_{\alpha+\beta} = \cos(\alpha) * \sin(\beta) + \sin(\alpha) * \cos(\beta)$$

$$S_{\alpha+\beta} = \cos(\alpha) * \sin(\beta) + \sin(\alpha) * \cos(\beta)$$

T^0 is the multiplication of matrices $T_1^0\, T_2^1\, T_3^2$.

How we can move mathematically T_3^0matrix to the matrix T_4^3.

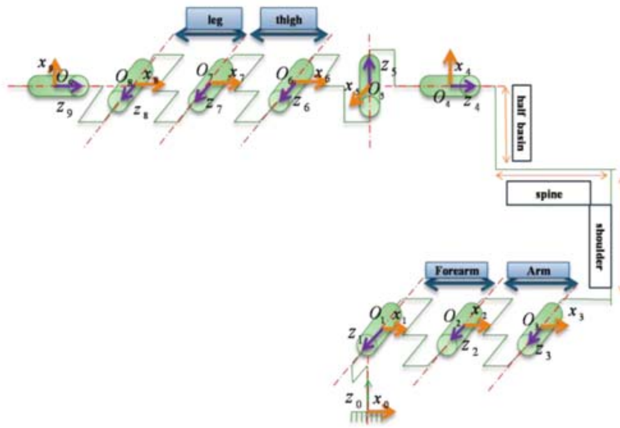

Figure 4. Direct geometrical modeling of the RH-ARP

We see that we have a sizable length of the shoulder, spine and pelvis half (review Figure 1). As we have a rotation of the axes x and z, the vector $x_{1.2.3}$ to the right and x_4 upwards, vector $z_{1.2.3}$ downwardly and the vector z_4 to the right.

We conclude that we must multiply the matrix T_3^0 by such a translation matrix and another rotation.

From Figure 1 we have sized our humanoid robot and we got a shoulder length equal to 22 cm, 50 cm for the spine and 32 cm for the pelvis half

So we get the translation matrix

$$L = \begin{bmatrix} 1 & 0 & 0 & X \\ 0 & 1 & 0 & Y \\ 0 & 0 & 1 & Z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 22 \\ 0 & 1 & 0 & 50 \\ 0 & 0 & 1 & 32 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The angle of rotation of the vector x1.2.3 to x4 is equal to 90°

The transformation matrix of rotation around the main axis is defined by:

$$ROT = rot(x, \theta) * rot(y, \theta) * rot(z, \theta)$$

$$A = rot(x, \theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$B = rot(y, \theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$C = rot(z, \theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The rotation matrix

$$R = A * B * C$$

$$R = \begin{bmatrix} C_\theta^2 & -C_\theta * S_\theta & S_\theta & 0 \\ C_\theta * S_\theta^2 + C_\theta * S_\theta & C_\theta^2 - S_\theta^3 & -C_\theta * S_\theta & 0 \\ S_\theta^2 - C_\theta^2 * S_\theta & C_\theta * S_\theta^2 + C_\theta * S_\theta & C_\theta^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

We have shown that we have a multiplication by the matrix translation and rotation matrix, but which first? As we all know, the matrix multiplication operation is not commutative!

According *wissama khalil* & *Etienne Dombre* [15]'' left multiplication transformation T^i_j means that the transformation is made with respect to the reference R_i. The multiplication is applied to the left translation and then rotated relative to the score R_i (reading from right to left of T^i_j)''.

We deduce that the left multiplication of the transformation T^0_9 means that the transformation is made with respect to the reference R_0 and applying the translation and rotation relative to the reference R_0 (reading from right to left T^0_9)

E is the translation matrix multiplied by the rotation matrix

$$E = L * R$$

$$E = L * R = \begin{bmatrix} C_\theta^2 & -C_\theta * S_\theta & S_\theta & X \\ C_\theta * S_\theta^2 + C_\theta * S_\theta & C_\theta^2 - S_\theta^2 & -C_\theta * S_\theta & Y \\ S_\theta^2 - C_\theta^2 * S_\theta & C_\theta * S_\theta^2 + C_\theta * S_\theta & C_\theta^2 & Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

To reduce the matrix T^0_3 on the matrix T^0_4 we multiply T^0_3 by E

$$T^0_{33} = T^0_3 * \mathrm{E}$$

$$T^0_{33} = \begin{bmatrix} 0 & S_{1+2+3} & C_{1+2+3} & a_2c_1 + \mathrm{zc}_{1+2} - \mathrm{YS}_{1+2+3} - \mathrm{XC}_{1+2+3} \\ -1 & 0 & 0 & -Z \\ 0 & S_3S_{1+2} - C_3C_{1+2} & S_{1+2+3} & a_2S_1 + \mathrm{ZS}_{1+2} - \mathrm{XS}_{1+2+3} - \mathrm{YC}_{1+2+3} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The homogeneous transformation matrices for the foot are:

$$T_4^3 = \begin{bmatrix} C_4 & -S_4 & 0 & 0 \\ S_4 & C_4 & -1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_5^4 = \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_5 & C_5 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_6^5 = \begin{bmatrix} C_6 & -S_6 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_6 & C_6 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_7^6 = \begin{bmatrix} C_7 & -S_7 & 0 & 35 \\ S_7 & C_7 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_8^7 = \begin{bmatrix} C_8 & -S_8 & 0 & 48 \\ S_8 & C_8 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_9^8 = \begin{bmatrix} C_9 & -S_9 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_9 & C_9 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

With Ci : Cosinus of θi, Si : Sinus of θi for other angles.

The total homogeneous matrix corresponds to the passage of the marker R_0 to R_9 mark is calculated by: T_9^0

$$T_9^0 = T_{33}^0 * T_4^3 * T_5^4 * T_6^5 * T_7^6 * T_8^7 * T_9^8 * T_8^7 * T_9^8$$

It is represented in the following form:

$$T_9^0 = \begin{bmatrix} x_x & y_x & z_x & p_x \\ x_y & y_y & z_y & p_y \\ x_z & y_z & z_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{cases} \mathrm{Px} = 25C_1 + 32C_{1+2} + 22C_{1+2+3} - 50S_{1+2+3} + 35(C_6 (S_5 C_{1+2+3} + C_5 S_4 S_{1+2+3}) - C_4 S_6 S_{1+2+3}) \\ -48(S_7 (S_6 (S_5 C_{1+2+3} + C_5 S_4 S_{1+2+3}) + C_4 C_6 S_{1+2+3}) + C_7 (C_6 (C_5 S_4 S_{1+2+3} - S_5 S_3 S_{1+2}) - C_4 S_6 S_{1+2+3})) \\ \mathrm{Px} = 25C_1 + 32C_{1+2} + 22C_{1+2+3} - 50S_{1+2+3} + 35(C_6 (S_5 C_{1+2+3} + C_5 S_4 S_{1+2+3}) - C_4 S_6 S_{1+2+3}) \\ -48(S_7 (S_6 (S_5 C_{1+2+3} + 50C_{1+2+3} + 25S_1 + 35(C_6 S_5 S_{1+2+3}) - C_5 (C_6 S_4 C_{1+2+3}) - C_4 S_6 S_{1+2+3})) \\ \mathrm{Pz} = 22S_{1+2+3} + 32S_{1+2} + 22C_{1+2+3} - 50S_{1+2+3} + 35(C_6 (S_5 C_{1+2+3} + C_5 S_4 S_{1+2+3}) - C_4 S_6 C_{1+2+3}) \\ -48(S_7 (S_6 (S_5 (S_4 C_{1+2+3}) + C_4 C_6 (C_3 C_{1+2} + S_3 S_{1+2})) + C_7 (C_6 (S_5 S_{1+2+3} - C_5 S_4 C_{1+2+3}) - C_4 S_6 C_{1+2+3} \end{cases}$$

5.3 Inverse geometrical model of RH-ARP

We have to calculate the inverse geometrical model for both feet only, considering the trunk of the robot as a base.

Each foot is composed of 6 DOF; we fixed 4DOF to calculate the matrix inverse geometric model.

5.4 Direct geometric of a leg

The total homogeneous matrix is:

$$T_4^0 = T_1^0 * T_2^1 * T_3^2 * T_4^3$$

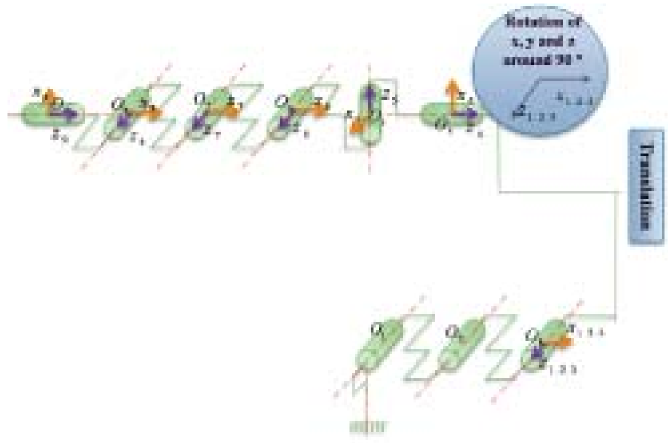

Figure 5. Representation of change of reference

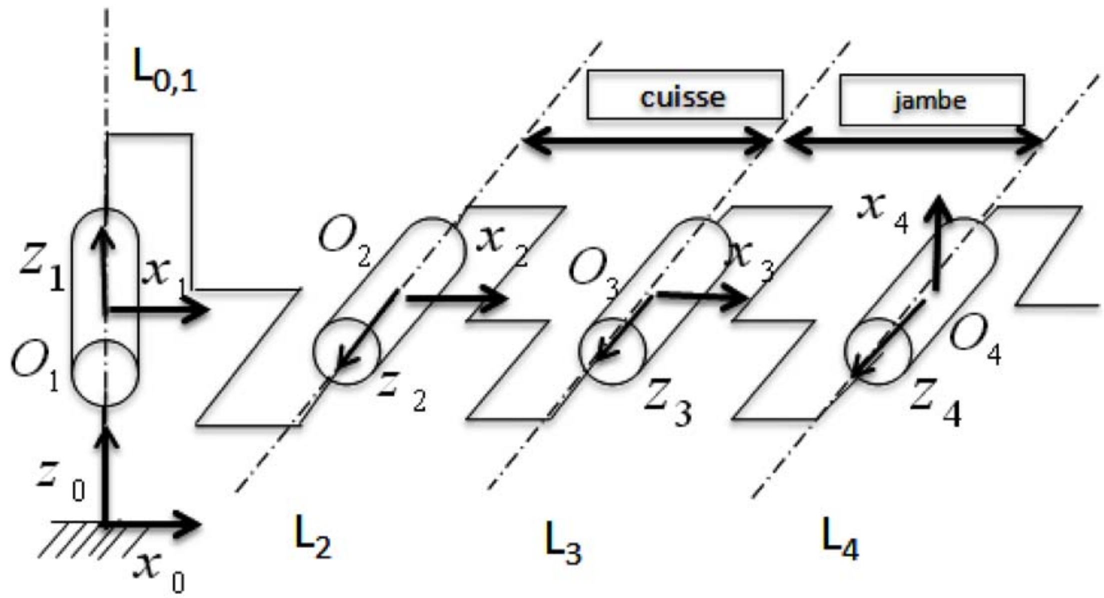

Figure 5. Direct geometrical modeling of the RH-ARP

With:

$$T_1^0 = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & -1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^1 = \begin{bmatrix} C_2 & -S_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} C_3 & -S_3 & 0 & a_2 \\ S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_4^3 = \begin{bmatrix} C_4 & -S_4 & 0 & a_3 \\ S_4 & C_4 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

We realize the matrix product:

$$T_4^0 = T_1^0 * T_2^1 * T_3^2 * T_4^3$$

We obtain a direct geometrical model which represents the fourth column of the matrix which makes it possible to describe the position of the final body: T_4^0

$$T_4^0 = \begin{bmatrix} C_1 * C_{2+3+4} & S_1 & C_1(a_3 * C_{2+3} + a_2 * C_2) \\ S_1 * C_{2+3+4} & -C_1 & S_1 * (a_3 * C_{2+3} + a_2 * C_2) \\ S_{2+3+4} & 0 & a_3 * S_{2+3} + a_2 * S_2 \\ 0 & 0 & 1 \end{bmatrix}$$

Calculation of the geometrical inverse model of the robot:

This model is the inverse of the precedent, for each position we have four angles to calculate $\theta 1$, $\theta 2$, $\theta 3$, $\theta 4$ for each articulation, where we had the possibility to find several solutions:

From the direct geometric of robot equation (1) we obtain

$$Xx = C_1 * C_{2+3+4} \tag{1}$$

$$Xy = -S_1 * C_{2+3+4} \tag{2}$$

$$Xz = S_{2+3+4} \tag{3}$$

$$Zx = S_1 \tag{4}$$

$$Zy = -C_1 \tag{5}$$

$$Zz = 0 \tag{6}$$

$$Px = C_1 * (a_3 * C_{2+3} + a_2 * C_2) \tag{7}$$

$$Py = S_1 * (a_3 * C_{2+3} + a_2 * C_2) \tag{8}$$

$$Pz = a_3 * C_{2+3} + a_2 * S_2 \tag{9}$$

Calculation of θ :

From (1) and (2) we obtain:

$$tg(\theta 1) = (Y / X) \qquad (10)$$

With:

$$\begin{cases} \theta_1 = arctg\,(Y/X)\; si\; \mathrm{X} \geq 0 \\ \theta_1 = arctg\,(Y/X) + \pi\, si\; \mathrm{X} < 0 \end{cases} \qquad (11)$$

Calculation of $\theta 3$:

We poses

$$\begin{cases} A = (X/C_1) \\ B = \mathrm{Z} \end{cases} \Rightarrow \begin{cases} A = C_{2+3} + a_2 * C_2 & (12) \\ B = a_3 * S_{2+3} + a_2 * S_2 & (13) \end{cases}$$

From (12) and (13) with squaring we obtain:

$$C_3 = (A^2 + B^2 - a_2^2 - a_3^2) / (2 * a_2 * a_3) \Rightarrow S_3 = \pm (1 - C_3^2)^{\frac{1}{2}}$$

$$\theta_3 = ATAN\,2\,(\pm (1 - C_3^2)^{\frac{1}{2}}, C_3)$$

Calculation of $\theta 2$:

$$S_2 = (a_2 + a_3 * C_3) * Z - a_3 * S_3 * (\mathrm{Y} / \mathrm{S}_1)) / a_2^2 + a_3^2 + 2\, a_2 + a_3)$$

$$C_2 = ((a_2 + a_3 * C_3)\,(\mathrm{Y} / \mathrm{S}_1) + a_3 * S_3 * Z) / a_2^2 + a_3^2 + 2\, a_2 + a_3)$$

$$\theta_3 = ATAN\,2\,(S_2, C_2)$$

Calculation of $\theta 4$:

$$\theta_4 = arctg2\,(S_1 * Xz / Xy) - (\theta_2 + \theta_3)$$

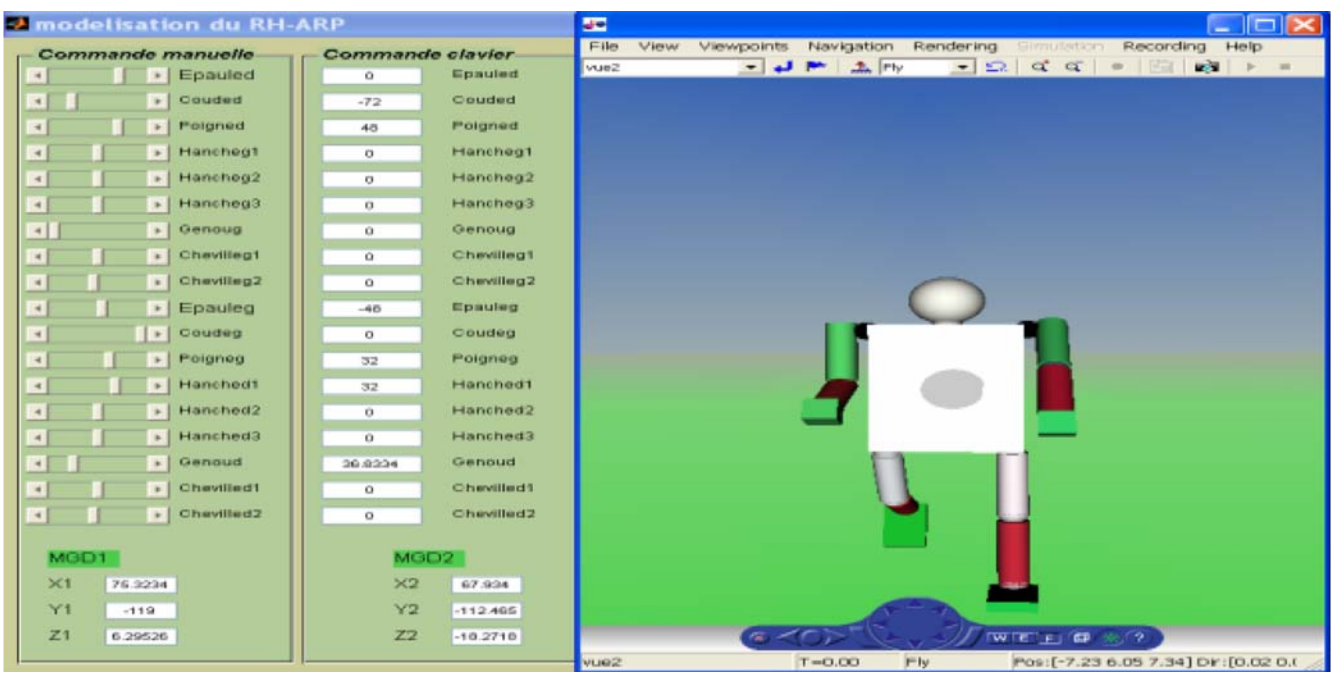

Figure 6. The position of paw according to X, Y, Z

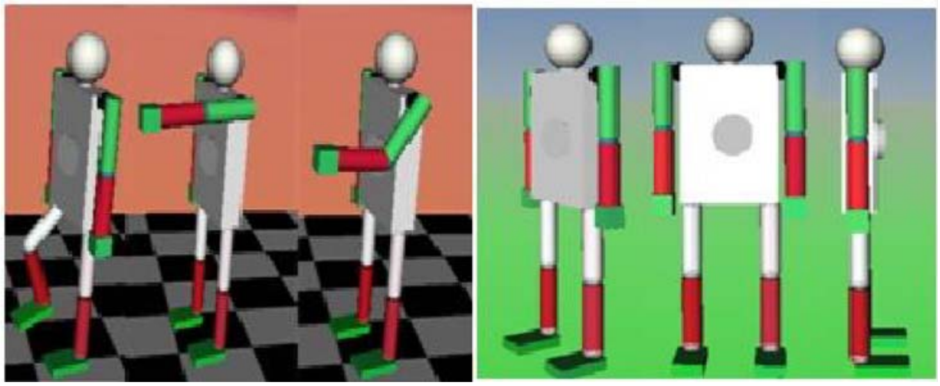

Figure 7 .Various movements and general views of the humanoid robot

6. Results and Simulations Interface

The figure 7 shows an interface done with VRML and programmed by MATLAB, it contains both manual and key board control, that allow to enter the angle of rotation value of the robot's articulation; and we can obtain the position of arm/leg on (X, Y, Z)axis from a program in the interface. See figure below.

We can see in this figure a general views of the humanoid robot and that he can do three articulations actions: rises its left arm, its left shoulder and its right leg.

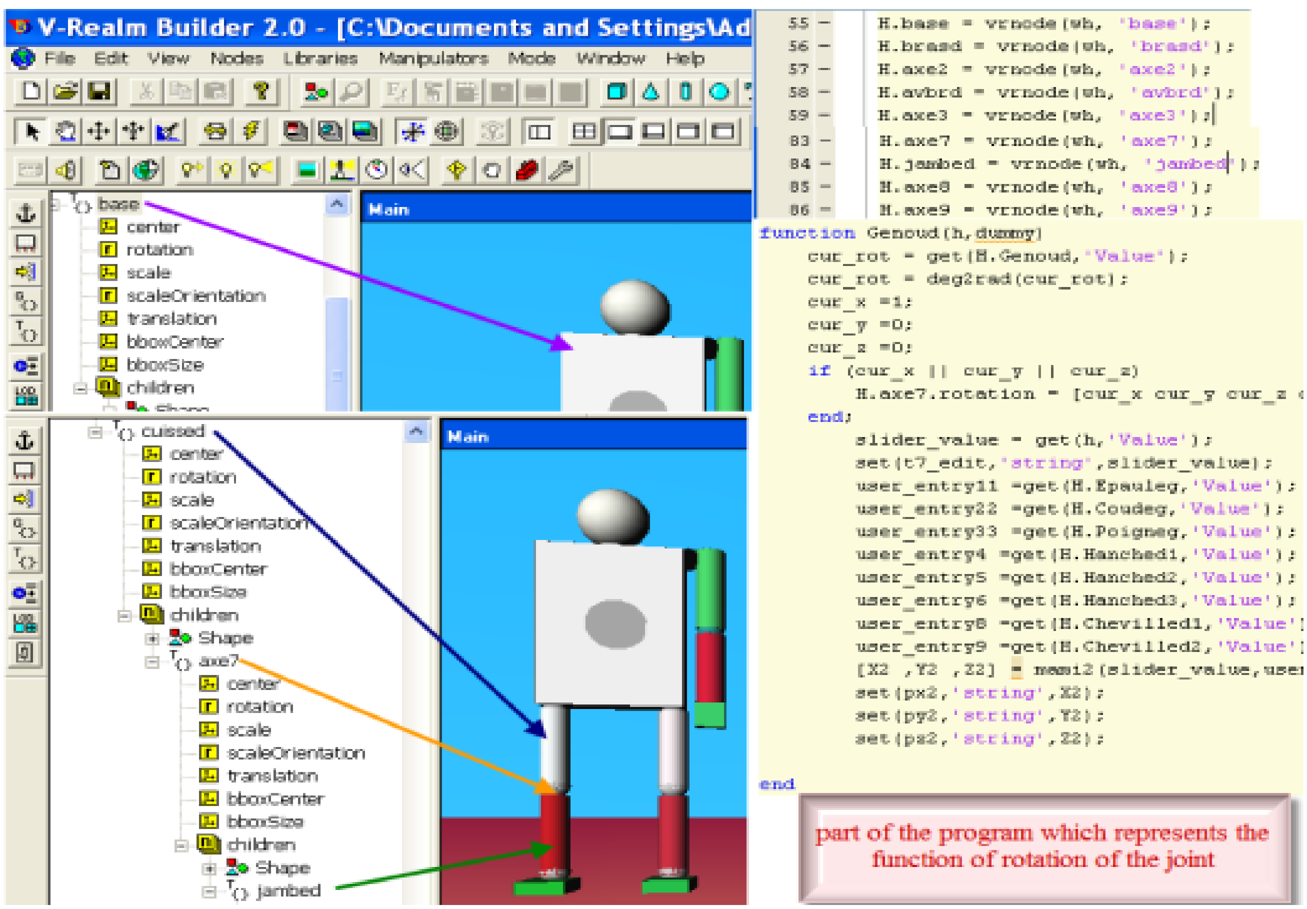

Figure 7. Different steps of drawing the humanoid robot with vrml

We started with the trunk which is a removable box and we chose the cylinder to draw the pates (arm-forearm-thigh-leg) and the sphere to show the knee joints, hip, shoulder, etc ...

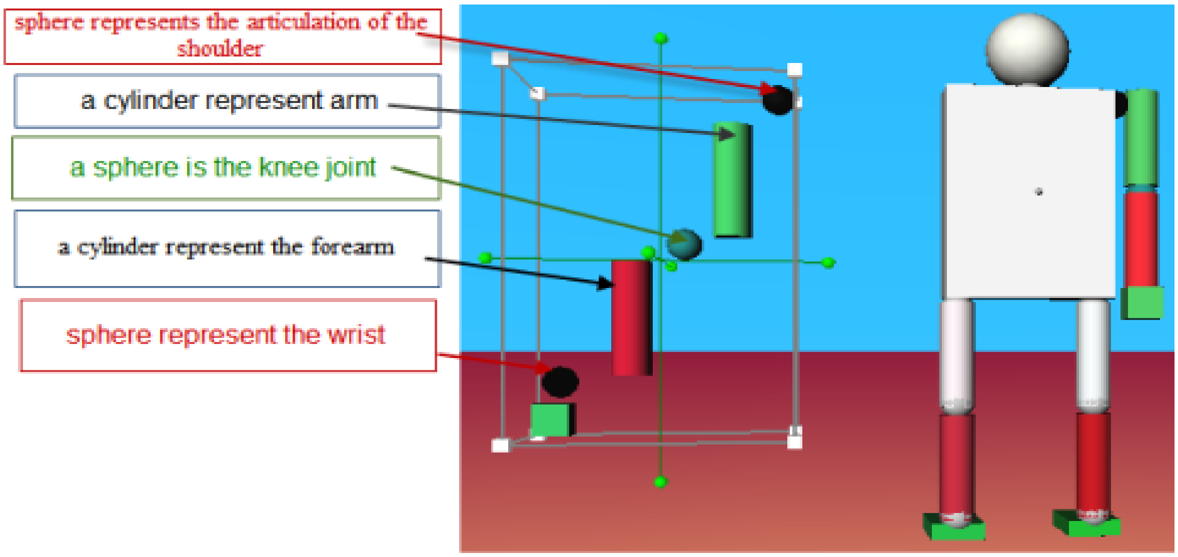

Figure 8. The different parties of the hand in vrml

We distinguish in the figure, the shoulder joint of the neck and wrist.

7. Conclusion

Building a robot may appear somewhat mundane rather than exotic, but it is far from trivial since many technologies have to be involved.

In kinematics, the D-H convention was employed to analyze the motion of the robot and to obtain its analytic expression. One difficulty in the analysis of kinematics of a robot is that managing its formulas becomes strenuous as the degree of freedom increases. It is cumbersome to check the correction of formulas even using symbolic manipulators. Hence, the animation could be a complementary method.

Although the advantage of using animation in kinematics is undeniable, it can't be trusted until the robot is truly built because some of the details can't be in our disposal in advance. In other words, the robotics is diversified in its nature. In this paper, we have presented the mechanical construction, kinematics and animation in building an upper humanoid robot.

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