Autonomous march control for humanoid robot animation in a virtual reality environment

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Abstract.- This article proposes an autonomous control scheme for the march of a humanoid robot applied to virtual reality environments. The control laws proposed for the autonomous displacement of a humanoid robot are based on their kinematic modeling, for which it is considered that the lower extremities of the robot have as reference the midpoint between the separation distance of the right and left leg, the same, what is related to the sacred bone of people. In order to validate the proposed control scheme, a virtual reality simulation environment is implemented, for which it is used as the Unity3D graphics engine.

Keywords: Path control, tracking control, virtual environment, humanoid robot, kinematic model.

1 Introduction

In the last decades, advances in industrial and service robotics have increased, being of great importance the creation of robots that can operate quickly, autonomously and with greater precision [1].In accordance to the locomotion capability the robots can be moved in various adverse environments, which can be mobile manipulator robots equipped with wheel-based displacement systems [2], or when the medium arrangement requires, legs, e.g. humanoid robot, spider robot and hexapod robot [3].

The humanoid is a robot designed to assimilate the body and movements of a human being and able to perform various functions, eg, open doors, remind a person to take their medicine, play soccer or dance [3], these are some of the functions that humanoid robots can perform at the moment, these actions can be done through a control scheme or with a programming software [4].

Researchers worldwide have worked on the development of humanoid robots in order to resemble humans and work together [5], therefore a direct and inverse kinematic model has been determined, for the legs of a humanoid robot Bioloid Premium with 12DOF in order to simulate the cycle of the march. The model starts from the selection of main and secondaries coordinates: main for the foot support and secondary for each joint of the links [6], in addition it is tried to develop a robot that allows to give it of mobility and autonomy, able to walk and to raise tiers, this project specifically focuses on the generation of trajectories, starting from an elementary scheme of a kinematic control system [7]. On the other hand, through the kinematic analysis is intended to present a humanoid robot with basic movement capabilities and with a minimum of actuators to walk, in this case a single motor to generate the movement path of the mechanism. Kinematic synthesis is based on the trajectories described by human movement [8].

This document establishes a control scheme which is composed of a path controller which allows the humanoid robot to have a high degree of autonomy at the moment of following the desired path; while the gait controller determines the step that each leg of the robot must perform, the control scheme is validated using a virtual reality tool, performing bilateral communication between mathematical software and virtual reality software.

2 Virtual Reality Environment

Virtual reality is a tool that can be used for the simulation of control schemes.
The 3D modeling of the humanoid robot is done in a tool (CAD). The structure of the humanoid robot presents an imitation of the human being so it has upper and lower limbs, which allow the autonomous march of the robot to be more real. The humanoid robot uses the geometric solid model that contains all the geometry of the surface, detailing the edges and faces of the model, [8] see Fig. 1.

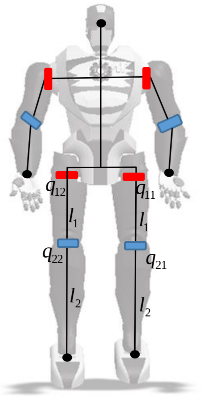


Fig. 1. Humanoid robot developed in Solidworks

The process to implement the 3D model of the proposed robot in a virtual reality environment is divided into the following stages: i) obtaining the 3D model, ii) adding hierarchies, iii) generation of the movement, and finally iv) animation of the humanoid robot for autonomous march control in a virtual reality environment, [8] see Fig. 2.

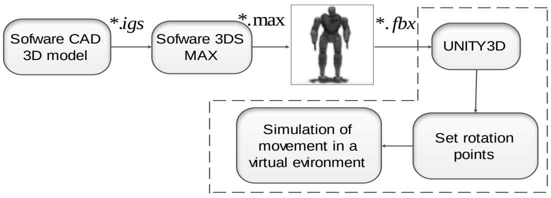


Fig.2 Process diagram

3 *Kinematic model of the legs*

To determine the kinematic model of the legs of the humanoid robot with 2 DOF, it is considered as a reference the midpoint between the distance of the right leg and the left, the same Which is denoted as $\{G\}$. This reference point is related to the sacral bone of the people, which is the moving point used for positioning and modeling each of the leg joints with respect to $\{G\}$. The analysis of the mechanism is performed as shown in Fig. 3.

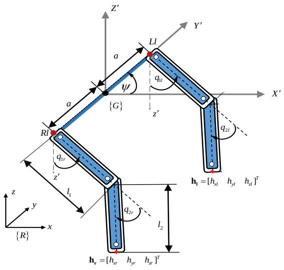


Fig.3. Kinematic of the legs of the humanoid

where, a represent the separation distances from a midpoint $\{G\}$ to the position of the right and left leg joint; l_1 is the length of the thigh and l_2 the length of the leg; ψ defines its orientation with respect to the Z axis of the inertial reference system $\{R\}$. Therefore the kinematic model of the right leg is given by,

$$\begin{cases} h_{xr} = x + aS_{\psi} + l_2 C_{q_{1r},q_{2r}} C_{\psi} + l_1 C_{\psi} C_{q_{1r}} \\ h_{yr} = y - aC_{\psi} + l_2 C_{q_{1r},q_{2r}} S_{\psi} + l_1 C_{q_{1r}} S_{\psi} \\ h_{zr} = h + l_2 S_{q_{1r},q_{2r}} + l_1 S_{q_{1r}} \end{cases} \tag{1}$$

where, q_{1r} and q_{2r} represents the position of the links of the right leg; $\mathbf{h_r} = \begin{bmatrix} h_{xr} & h_{yr} & h_{zr} \end{bmatrix}^T$ corresponds to the position of the end of the right leg.

Further, $S_{\alpha\beta} = Sen(\alpha+\beta)$, $S_{\alpha} = Sen(\alpha)$, $C_{\alpha\beta} = \mathrm{Cos}(\alpha+\beta)$, $C_{\alpha} = \mathrm{Cos}(\alpha)$. Deriving, the representation in matrix form is represented by,

$$\dot{\mathbf{h}}_r(t) = \mathbf{J}_r(q_r)\dot{\mathbf{q}}_r(t) \qquad (2)$$

Where, $\dot{\mathbf{h}}_{\mathbf{r}}(t) = [\dot{h}_{xr} \quad \dot{h}_{yr} \quad \dot{h}_{zr}]^T$ represents the velocities in the working space of the right foot; $\dot{\mathbf{q}}_r(t) = [\dot{q}_{1r} \quad \dot{q}_{2r} \quad \dot{\psi}]^T$ where, $\dot{q}_{1r}$ and $\dot{q}_{2r}$ are the angular speeds of maneuverability of the right leg; while $\dot{\psi}$ it is the change of orientation regarding the time of the hip with respect to $\{R\}$; and $\mathbf{J}_{\mathbf{r}}(q)$ represents the Jacobian matrix that relates the movement velocities of the joints.

Remark 1.- According to the above, to determine the kinematic model of the left leg is obtained with (1) and (2), but with the value of a sign changed. So the kinematic model is,

$$\dot{\mathbf{h}}_l(t) = \mathbf{J}_l(q_l)\dot{\mathbf{q}}_l(t) \qquad (3)$$

4 Control Scheme

In this section is present a control scheme composed of a path controller, which allows the robot to follow a desired path; and a march controller that determines the step of each leg of the robot, see Fig.4.

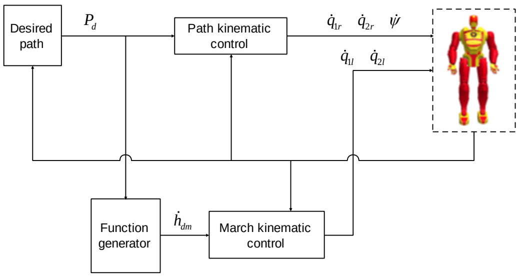


Fig. 4 Control subsystem in parallel in the k instant

Remark 2. - In a sampling period k the right leg reaches the desired position through the tracking controller, while with the path controller the left leg performs the gait; at the moment $k+1$ the controllers are inverted, i.e., the right leg performs the march while the left reaches a desired position of the road.

4.1 Track tracking control

As shown in Fig. 5, the way forward is called $P(s)$. The desired position is described with, $P_d = (P_{xd}, P_{yd})$ this point is defined as the closest point to $P(s)$, The unit vector tangent to the path at point P_d is denoted by T ; ψ_d is the orientation of T with respect to the X axis of $\{R\}$; $\tilde{h}_{xp} = P_{xd} - x$ is the position error in the X direction; $\tilde{h}_{yp} = P_{yd} - y$ is the position error in the Y direction; therefore ρ represents the distance between the position of the humanoid robot $h(x, y)$ and the desired point P_d. Where the position error in the direction ρ is $\tilde{\rho} = 0 - \rho = -\rho$, *i.e.,* The desired distance between the position of the robot $h(x, y)$ and the desired point P_d must be zero; ψ_ρ is the orientation of the error $\tilde{\rho}$ with respect to $\{R\}$.

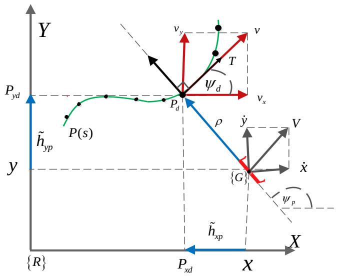


Fig. 5 Orthogonal projection of the point of interest over the trajectory.

To solve the problem of tracking path in the plane $X - Y$ of $\{R\}$ only the direct kinematics of the position in the axis is considered $X - Y$ of the right leg. The kinematic model that is determined for the robot to reach the path is represented by,

$$\begin{cases} h_{xrp} = x + aS_\psi + l_2 C_{q_{1r}, q_{2r}} C_\psi + l_1 C_\psi C_{q_{1r}} \\ h_{yrp} = y - aC_\psi + l_2 C_{q_{1r}, q_{2r}} S_\psi + l_1 C_{q_{1r}} S_\psi \end{cases} \quad (4)$$

Deriving (4), the representation in matrix form is presented by,

$$\dot{\mathbf{h}}_{\mathbf{rp}}(t) = \mathbf{J}_{rp}(q_{rp})\dot{\mathbf{q}}_{\mathbf{rp}}(t) \quad (5)$$

where $\dot{\mathbf{h}}_{\mathbf{rp}}(t)=[\dot{h}_{xrp} \quad \dot{h}_{yrp}]^T$ represents the speeds in the plane $X-Y$ of the system $\{R\}$; and $\mathbf{J}_{\mathbf{rp}}$ represents the Jacobian matrix that relates the velocities of $\dot{q}_{1rp}(t)$ with respect to the linear speeds in the plane $X-Y$ of $\{R\}$.
The proposed control law to solve the path-tracking problem is based on the inverse kinematics of (5).

$$\mathbf{V}_{\mathbf{r}}(t)=\mathbf{J}^{\#}_{\mathbf{rp}}\left(\mathbf{V}_{\mathbf{xyd}}+\mathbf{K}_p \tanh\left(\tilde{\mathbf{h}}_{\mathbf{p}}\right)\right) \qquad (6)$$

where, $\mathbf{J}^{\#}_{\mathbf{rp}}$ is the pseudoinverse Jacobian matrix on the right; $\mathbf{V}_{\mathbf{xyd}}=[v\cos(\psi_d) \quad vsen(\psi_d)]^T$ is the desired velocity vector of the path; $\mathbf{K}_{\mathbf{p}}$ is the diagonal matrix of positive gain for the compensation of the error generated; $\tanh(.)$ limits the reference speeds, thus avoiding the saturation of the speed of the robot; $\tilde{\mathbf{h}}_{\mathbf{p}}=[\tilde{h}_{xp} \quad \tilde{h}_{yp}]^T$ is the vector of errors defined with, $\tilde{h}_{xp}=P_{xd}-x$, $\tilde{h}_{yp}=P_{yd}-x$; $\mathbf{V}_{\mathbf{r}}(t)=\left[\dot{q}_{1rp} \quad \dot{q}_{2rp} \quad \dot{\psi}\right]^T$ represents the maneuverability vector of the system.

Remark 3.- According to the above, for $K+1$ the law of road control for the left leg is obtained with,

$$\mathbf{V}_{\mathbf{l}}(t)=\mathbf{J}^{\#}_{\mathbf{lp}}\left(\mathbf{V}_{\mathbf{xyd}}+\mathbf{K}_{\mathbf{p}} \tanh\left(\tilde{\mathbf{h}}_{\mathbf{p}}\right)\right) \qquad (7)$$

4.2 Control of the March

For control of the march of the humanoid robot, a reference system is determined with respect to $\{L_l\}$, which is located in the center of the thigh of the left leg, see Fig.3. According to the axis of reference the kinematic model is determined in order to determine a control law based on its kinematics. The kinematic model of the left leg with respect to $\{L_l\}$ this given by,

$$\begin{cases} h_{xrm}=l_1 C_{q_{1lm}}+l_2 C_{q_{2lm},q_{1lm}} \\ h_{zrm}=l_1 S_{q_{1lm}}+l_2 S_{q_{2lm},q_{1lm}} \end{cases} \qquad (8)$$

where, q_{1lm} and q_{2lm} represent the position of the left leg for the march, l_1 is the length of the thigh and l_2 the length of the leg. The trajectory that is generated is related to the end of the left leg in the position h_{zr} of the kinematic model (3), the parameters of the generated parabola are varied in amplitude and angular frequency according to the desired step. Performing the derivate of (8) the matrix form of the kinematic model is represented by,

$$\dot{\mathbf{h}}_{lm}(t)=\mathbf{J}_{lm}(q_{lm})\dot{\mathbf{q}}_{lm}(t) \tag{9}$$

where $\dot{\mathbf{h}}_{\mathbf{lm}}(t)=\left[\dot{h}_{xlm} \quad \dot{h}_{zlm}\right]^T$ represents the velocities in the working space of the left foot with respect to $\{L_l\}$; $\dot{\mathbf{q}}_{\mathbf{lm}}(t)=[\dot{q}_{1lm} \quad \dot{q}_{2lm}]^T$ where, $\dot{q}_{1lm}$ and $\dot{q}_{2lm}$ are the angular velocities of maneuverability of the left leg; and $\mathbf{J}_{\mathbf{lr}}$ represents the Jacobian matrix of the left leg that relates the joint movement velocities.
The control law proposed according to the kinematic model of the left leg of the humanoid robot is given by,

$$\dot{\mathbf{q}}_{\mathbf{lm}}(t)=\mathbf{J}^{\mathbf{-1}}_{\mathbf{lm}}\left(\dot{\mathbf{h}}_{\mathbf{dm}}+\mathbf{K}_m\tanh\left(\tilde{\mathbf{h}}_m\right)\right) \tag{10}$$

where, $\mathbf{J}^{\mathbf{-1}}_{\mathbf{lm}}$ is the inverse Jacobian matrix of the left leg; $\dot{\mathbf{h}}_{\mathbf{dm}}(\mathbf{t})=\left[\dot{h}_{xdt} \quad \dot{h}_{zdt}\right]^T$ is the vector of the desired velocities, i.e., the left leg foot; $\mathbf{K}_{\mathbf{m}}$ is the gain constant for the compensation of the error generated; $\tanh(.)$ limits the reference speeds, thus avoiding the saturation of the speed of the robot; $\tilde{\mathbf{h}}_{\mathbf{m}}(t)=\left[\tilde{h}_{xm} \quad \tilde{h}_{zm}\right]$ is the vector of errors defined as $\tilde{h}_{zm}=h_{zd}-h_{zr}$, while to determine the error $\tilde{h}_{xm}$ is considered $\tilde{h}_{xm}=|V|f+|E|g$, where $|V|=\sqrt{(v_x)^2+(v_y)^2}$,$|E|=\sqrt{(\tilde{h}_{xp})^2+(\tilde{h}_{yp})^2}$, f y g, are constant of error adjustment.

Remark 4.- According to the above, the kinematic model of the right leg respect $\{L_r\}$ of the humanoid robot with (9) is,

$$\dot{\mathbf{h}}_{\mathbf{rm}}(t)=\mathbf{J}_{\mathbf{rm}}(q_{rm})\dot{\mathbf{q}}_{\mathbf{rm}}(t) \tag{11}$$

In addition, the law of march control that is presented for the right leg of the humanoid robot is obtained with (11).

$$\dot{\mathbf{q}}_{\mathbf{rm}}(t) = \mathbf{J}_{\mathbf{rm}}^{-1}\left(\dot{\mathbf{h}}_{\mathbf{dm}} + \mathbf{K}_m \tanh\left(\tilde{\mathbf{h}}_m\right)\right) \tag{12}$$

Remark 5. - From the analysis of the errors of the controllers, previously exposed, they are concluded that they tend asymptotically to zero when $t \to \infty$, as demonstrated in [9].

5 Results

Fig. 9 shows strobe motion in a virtual reality environment, which allows verifying the autonomous functioning of the humanoid robot.

Fig. 9 Stroboscopic movement of the humanoid robot

According to the proposed control scheme, Fig. 10 illustrates the path made by each leg of the humanoid robot and shows the path tracking of the robot when it reaches the desired position.

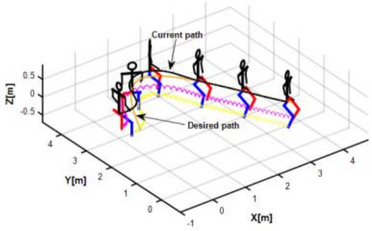
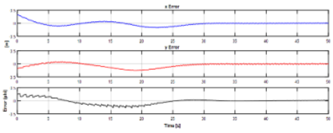


Fig. 10 Path of the step and track of road

Fig. 11 (a) shows position and orientation errors of the path controller at the midpoint $\{G\}$, while Fig. 11 (b) illustrates the path controller errors that are generated at the time of the gait step is done.



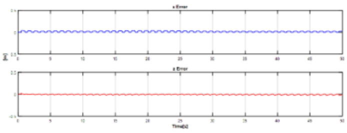


Fig.11 (a) Errors of the road **Fig.11** (b) Errors in the Trajectory of the march

6 Conclusions

In this article, a control scheme is presented which includes *i) a control algorithm for the path tracking* so that the humanoid robot follows a desired path; and *ii) a trajectory tracking control algorithm* which allows the robot to perform the march at the moment it travels to the path. The controllers presented are based on the kinematics of the robot, which fulfill the purpose of generating movement and displacement. In addition, simulations were implemented in a virtual reality environment in order to evaluate the performance of the proposed control scheme, which shows the development od the movement of the lower extremities of the humanoid robot towards the path and the gait that it executes int the instant of movement, through Which can be verified that it is possible that the humanoid robot carries out the autonomous march.

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