Method of Omnidirectional Movement of Humanoid Robot

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Abstract. In order to solve the problems in the high computation, mono moving direction, low real time effect when switching gaits and unstable switching steps, etc., a fast computing method for omnidirectional motion planning of humanoid robot is proposed. The motion planning based on module design helps to obtain the moving trajectories in directions and the direction-switching algorithm based on one of multiple steps of segments helps to interconnect directional movements and realize the stability and fluency. The validity of method is proved by experiments.

Introduction

The humanoid robot is a multi-degree free, nonlinear, strong-coupling, structure-changing and complicated dynamical system with two feet supporting. Compared with the other motion modes such as the wheel mode, the creep mode and the multi-feet mode, it has a stronger adaptability of omnidirectional movement [1~2]. The humanoid robot not only meets the requirement of stabling gaits in any direction but can also switch the moving direction and moving speed flexibly in real time. Omnidirectional movement is the basic for the humanoid robot to operate effectively in complicated environments and to make decisions by itself. This process involves with the multi body dynamics model, the complex kinematics and the Dynamic calculation. The article [3] adopts the multipurpose kinematics parameters to describe the single step motion process of the robot, puts forward the transition algorithm of the steps, solves the problems of connecting steps and realizes the omnidirectional movement of the humanoid robot. By using the pre-observation control method the articles [4-7] solve the motion trajectories of the robot’s hip and produce the joint trajectories of any step parameters, which helps to control the omnidirectional movement of humanoid robot and to make the omnidirectional moving gaits follow any step instruction. The article [8] uses the central pattern generator (CPG) to describe every joint trajectory by applying a periodic function, adjusts the function parameters according to the step instructions and realizes omnidirectional movement in the loop experiment. The article [9] puts forward a quick path planning strategy based on state grid plans for omnidirectional moving robots. The strategy helps to produce an effective path of two-feet moving for robots and finishes the quick path planning for humanoid robots in the dynamic environment. The article [10] introduces the gait unit into the movement planning for humanoid robot. According to the differential equation of inverted pendulum motion, in the repeated period of two-feet moving, changing the initial conditions and connecting the same unit gait to produce the robot’s trajectories.

The above researches realize the omnidirectional movement of humanoid robot to some extent. But the costs of path planning and the control algorithm computation are too high. The real time effect is low. The key to omnidirectional movement path planning is the robot can change from the current gait to other gaits flexibly, freely and naturally when switching its gaits in a sudden. The path planning in each direction is interdependent while the robot’s stability is kept. (For example, when the robot is moving ahead, it involves with six degrees of freedom, such as the pitch of the hip joint, the knee joint and the ankle joint completing the movement. While the robot is conducting the sideway movement, it relates with four degrees of freedom of two feet, which are the deflection of
the hip joint and the ankle joint.) Based on the facts mentioned above, in order to reduce the computation cost and simplify the computation, the article [10] optimizes the single step method. According to the kinematical limit of each main joint while switching gaits, with an analysis of dynamics, one of multiple steps of segments is used to make the robot change from the current direction to the expected direction to complete the moving direction-switching transition algorithm.

**Description of Models of Humanoid Robot**

**Three-dimensional Linear Inverted Pendulum Model**

Moving in a three-dimensional space, the humanoid robot is equal to an inverted pendulum model formed by a particle which centralizes the robot’s whole weight and a weightless foot connecting the particle with the supporting point (11). As the Figure 1 shows, the supporting point is the joint of the robot’s leg. The moment is zero. It can move freely. Supposed there is a contractility $f$ on the supporting leg. The length of the leg is changeable.

![Figure 1 Three-dimensional Linear Inverted Pendulum.](image)

The contractility $f$ is on the robot’s leg, which has the same effect of the robot’s knee joint stretching or bending. With the effect of the gravity and the contractility, the COM (Center of Mass) moves with the contractility. According to the dynamics, it can be concluded that

\[
\begin{align*}
M\ddot{x} &= \left(\frac{x}{r}\right)f \\
M\ddot{y} &= \left(\frac{y}{r}\right)f \\
M\ddot{z} &= \left(\frac{z}{r}\right)f - Mg
\end{align*}
\]

$\ddot{r}$ is the distance between the COM to the supporting point. $g$ is the gravity acceleration. $x, y$ and $z$ are the spatial coordinates.

![Figure 2. Inverted Pendulum Model of Robot.](image)

**Description of Model for Humanoid Robots**

The linear inverted pendulum model does not consider the rotational inertia, the mass of the swing leg and the friction as well as coupling of joints. So it cannot reflect the dynamic characteristics of
connecting rods, such as the robot’s legs. The robot’s connecting rod model can make up for the deficiency of the inverted pendulum model. Taking the humanoid robot’s moving characteristics into account, based on the following ideal conditions\textsuperscript{[12]}: (1) Both the hip and the sole are parallel with the ground. (2) The height of the COM is unchanged. (3) The robot’s rotational inertia is small enough to be omitted when moving. So the seven connecting rod optimization model based on the inverted pendulum model can be adopted as the Figure 2 shows. P represents the upper part of the body (including the head, arms and the body).

In the study of the humanoid robot’s gaits, the three-dimensional inverted pendulum model is usually seen as a combination of two two-dimensional inverted pendulum models in the XOZ and in the YOZ planes\textsuperscript{[13-14]}. \(f_x, f_y\) and \(f_z\) are the component forces of the contractility \(f\) in the \(X, Y\) and \(Z\) direction respectively in the spatial coordinates. \(F_X, F_Y\) and \(F_Z\) represent the three components of the moment of the COM receiving the reacting force from the ground in the in the \(X, Y\) and \(Z\) direction respectively in the spatial coordinates. For the \(X\) and \(Y\) axis, according to an analysis of the moment, the differential equation is

\[
\begin{align*}
(F_y + Mg_x &= Mz\ddot{x} - Mx\ddot{z} \\
(F_x - Mg_y &= My\ddot{y} - Mz\ddot{y})
\end{align*}
\]

\(x, y\) and \(z\) are the coordinates of the COM. \(M\) is the mass of the COM. \(g\) is the gravity acceleration. \(F_x\) and \(F_y\) are the active moment produced by the outside force for the robot. Based on the idea of the energy optimization, \(F_x, F_y\) and \(\ddot{z}\) are equivalent to zero, then

\[
\begin{align*}
\ddot{x} &= \frac{g}{z} x \\
\ddot{y} &= \frac{g}{z} y
\end{align*}
\]

According to the Laplace transform solution differential equation, the trajectory equation of the robot’s COM is

\[
\begin{align*}
x(t) &= x(0) \cosh\left(\frac{t}{T}\right) + T\ddot{x}(0) \sinh\left(\frac{t}{T}\right) \\
y(t) &= y(0) \cosh\left(\frac{t}{T}\right) + T\ddot{y}(0) \sinh\left(\frac{t}{T}\right) \\
\ddot{x}(t) &= \frac{x(0)}{T} \sinh\left(\frac{t}{T}\right) + \ddot{x}(0) \cosh\left(\frac{t}{T}\right) \\
\ddot{y}(t) &= \frac{y(0)}{T} \sinh\left(\frac{t}{T}\right) + \ddot{y}(0) \cosh\left(\frac{t}{T}\right)
\end{align*}
\]

\(T = \sqrt{z/g}\), a constant, is the root of the ratio of the COM’s height and gravity acceleration. \(x(0)\) and \(\ddot{x}(0)\) are the initial displacement and initial speed of the COM in the \(X\) axis. \(y(0)\) and \(\ddot{y}(0)\) are the initial displacement and initial speed of the COM in the \(Y\) axis. Given the initial condition, the trajectory of the COM and the other joints of the leg are certain\textsuperscript{[15]}.

**Trajectory Planning of Omnidirectional Movement**

**Forward and Backward Gait.** The robot’s moving process can be divided into the supporting phrase and the swing phrase. The consecutive switching of the two phrases forms the trajectory of the robot. The trajectory of the gait unit in the space is a hyperbola which produces symmetry about the \(Y\) axis. Given the initial displacement of the robot, the gait unit can be solved by the position of the ending state. Therefore, supposed the position of the initial state is \((-X, Y, 0\) with the speed \((\dot{X}, -\dot{Y})\) and \(T_s\) being the time that the leg is in the supporting state in the gait unit, then the position \((X,Y)\) and the speed \((\dot{X}, \dot{Y})\) of the ending state are

\[
X = (-X) \cosh\left(\frac{T_s}{\sqrt{z/g}}\right) + \sqrt{z/g} \dot{X} \sinh\left(\frac{T_s}{\sqrt{z/g}}\right)
\]
\[
Y = Y \cosh \left( \frac{T_s}{\sqrt{z/g}} \right) + \sqrt{\frac{z}{g}} \left( -\dot{Y} \right) \sinh \left( \frac{T_s}{\sqrt{z/g}} \right) \tag{7}
\]

\[
\dot{X} = \left[ X \cosh(T_s/\sqrt{z/g}) + x \right] / \left[ \sqrt{z/g} \sinh(T_s/\sqrt{z/g}) \right] \tag{8}
\]

\[
\dot{Y} = \left[ Y \cosh(T_s/\sqrt{z/g}) - y \right] / \left[ \sqrt{z/g} \sinh(T_s/\sqrt{z/g}) \right] \tag{9}
\]

When the humanoid robot is moving forward, the positions of the foothold change accordingly. At some moments of the omnidirectional movement, the robot needs to be in the expected position. The location can be acquired by setting the length and the width of the gait, then

\[
\begin{bmatrix} P_x^{(n)} \\ P_y^{(n)} \end{bmatrix}^T = \begin{bmatrix} P_x^{(n-1)} + L_x^{(n)} \\ P_y^{(n-1)} + (-1)^n L_y^{(n)} \end{bmatrix}^T \tag{10}
\]

\((P_x^{(n)}, P_y^{(n)})\) is the location of the \(n^{th}\) step. \(L_x^{(n)}\) is the length of the gait on \(X\) axis. \(L_y^{(n)}\) is the width of the gait on \(Y\) axis. The length and the width of the \(n^{th}\) step are

\[
\begin{bmatrix} X^{(n)} \\ Y^{(n)} \end{bmatrix}^T = \begin{bmatrix} L_x^{(n)}/2 \\ (-1)^{n+1} L_y^{(n+1)}/2 \end{bmatrix} \tag{11}
\]

The length and the width of the \(n^{th}\) step are determined by the length and the width of the \((n+1)^{th}\) step.

The backward movement of the humanoid robot is in fact the opposite movement of the forward movement. Because of the limited space, the reasons will be not listed here. Considering the stability and the characteristics of the humanoid movement, the length of the gait backward should be shorter than that of the gait forward.

Figure 3. The Track Schematic of Humanoid Robot Moving Forward and Backward.
Figure 4. The Forward Basic Posture of Humanoid Robot.

In order to move stably and to plan the moving pose, neglecting the influence of the inertial force, the robot’s basic poses of moving forward are: (1) The upper body is always perpendicular to the ground; (2) The distance between the hip joint and the ground is unchanged to stable the height of the COM. (3) The supporting leg must locate in the stable area of the ZMP (Zero moment point) and the swinging height of the swing leg reaches maximum. (4) The sole is parallel to the ground.

In the following description of the sideway moving and the turning, the robot keeps the above poses.

**Sideway Moving Gait.** The sideway moving refers to swing the COM by rolling the ankle joint and the hip joint in the YOZ plane in the spatial coordinates. The solution to the trajectory planning is similar to the moving trajectory planning. The difference lies in that when changing the supporting leg to the swing leg, the COM must swing within the stable area of the supporting leg. The trajectory is shown in Figure 5.

As Figure 6 shows, in the process of sideway moving, the angle between the swing leg’s ankle joint and the hip joint with the ground is equal to the angle between the supporting leg’s ankle joint and the hip joint with the ground. In other words, $|\Phi_6|=|\Phi_7|$, $|\Phi_8|=|\Phi_9|$.

Figure 5. Sideway Moving Gait of Robot.

Figure 6. Basic Pose of Sideway Moving for Robot.
**Turning Planning.** When planning the turning direction of the humanoid robot, the forward movement planning is used as a reference. By adding the pre-setting turning angle \( \theta \), modifying the location, the length of the gait, the width of the gait and the velocity equation, the equation for the robot’s turning can be obtained.

The location of the \( n \)th step:

\[
\begin{bmatrix}
P_x^{(n)} \\
P_y^{(n)}
\end{bmatrix} = \begin{bmatrix}
P_x^{(n-1)} \\
P_y^{(n-1)}
\end{bmatrix} + \begin{bmatrix}
cos(\theta^{(n)}) & -sin(\theta^{(n)}) \\
sin(\theta^{(n)}) & cos(\theta^{(n)})
\end{bmatrix} \begin{bmatrix}
L_x^{(n)} \\
L_y^{(n)}
\end{bmatrix}
\]

(12)

The length and the width of the \( n \)th step:

\[
\begin{bmatrix}
X^{(n)} \\
Y^{(n)}
\end{bmatrix} = \begin{bmatrix}
\frac{cos(\theta^{(n+1)})}{sin(\theta^{(n+1)})} & -\frac{sin(\theta^{(n+1)})}{cos(\theta^{(n+1)})}
\end{bmatrix} \begin{bmatrix}
\frac{L_x^{(n+1)}}{2} \\
\frac{L_y^{(n+1)}}{2}
\end{bmatrix}
\]

(13)

The ending speed of the \( n \)th step:

\[
\begin{bmatrix}
X^{(n)} \\
Y^{(n)}
\end{bmatrix} = \begin{bmatrix}
\frac{cos(\theta^{(n+1)})}{sin(\theta^{(n+1)})} & -\frac{sin(\theta^{(n+1)})}{cos(\theta^{(n+1)})}
\end{bmatrix} \begin{bmatrix}
\frac{X \cosh(T \sqrt{z/g}) + X}{\sqrt{z/g}} \sinh(T \sqrt{z/g}) \\
\frac{Y \cosh(T \sqrt{z/g}) - Y}{\sqrt{z/g}} \sinh(T \sqrt{z/g})
\end{bmatrix}
\]

(14)

Figure 7. Trajectory of Robot Turning.

**Conversion and Linkage of Moving Direction.** The article [15] states that if the humanoid robot stops within a step while it is moving, the robot will lose the balance and fall down. Therefore, when changing the direction in a sudden, the robot has difficulty in changing it and walking stably in a single step. In order to solve the problem, the multi-steps switching segment interpolation is introduced. The segment interpolation is conducted during the period of two legs supporting when switching between two directions. By adjusting the angles of every joint to obtain the consecutive moving trajectory of each moving joint, the robot completes the transition from the previous direction to the expected direction stably and flexibly with one or multiple steps.

If the angle between the previous direction and the expected direction is relatively small, the robot can change the direction flexibly and stably within a step. Suppose \( \theta_0 \), \( \theta_m \) and \( \theta_f \) are the angles of the initial moment, the middle moment and the ending moment when the humanoid robot is changing directions. \( L_0 \) is the distance between the hip joint and the supporting point. The position parameters of the pre-setting changing initial moment and the ending moment are set, then the position is constrained to

\[
H(\theta) = \begin{cases}
L_0(P_x^0, P_y^0), & \theta = \theta_0 \\
L_0(P_x^m, P_y^m), & \theta = \theta_m \\
L_0(P_x^f, P_y^f), & \theta = \theta_f
\end{cases}
\]

(15)

In order to meet the continuity of the moving velocity, the velocities of the initial moment and the ending moment when the robot is changing direction are constrained to
\[ \dot{H}(\theta) = \begin{cases} (v_x^0, v_y^0), & \theta = \theta_0 \\ (v_x^f, v_y^f), & \theta = \theta_f \end{cases} \] (16)

Based on the constrain conditions of (21) and (22), in order to acquire the consecutive moving trajectory, making the function \( H(\theta) \) a cubic polynomial, then

\[ H(\theta) = \begin{cases} a_0^0 + a_0^1 \theta + a_0^2 \theta^2 + a_0^3 \theta^3, & \theta \in [\theta_0, \theta_m) \\ a_f^0 + a_f^1 \theta + a_f^2 \theta^2 + a_f^3 \theta^3, & \theta \in [\theta_m, \theta_f) \end{cases} \] (17)

\( a_0^i \) and \( a_f^i \) are correlation coefficients, which can be solved by the function \( H(\theta) \)'s first-order derivative and the second-order derivative in \( \theta_m \).

If the angle between the previous direction and the expected direction is relatively large, being constrained by the moment of the joints, the drive from the joints might not be able to provide the moment big enough to complete the switching in a step. The robot needs to finish to direction switching in multiple steps. The idea is that in the feasible parameter field, the angle is divided into several angles of the moments that each humanoid joint can provide and complete the direction switching by multiple one-step switching. In addition, with the influence of the inside and outside constraint conditions, the switching angles and the moments of joints must be constrained in a range that the robot can bear to avoid the phenomenon such as the angle of the joint over-speeding and the supporting leg slipping on the ground because the constraint conditions are destroyed.

**Experiments**

The simulation platform Simulink of the software Matlab is adopted to simulate the omnidirectional movement. The structure of the model is shown in Figure 8. SimMechanics is used to model the humanoid robot. The coordinates of the connecting rod of each part apply the coordinates of the COM of the main body as references. The design of the module diagram and the related parameters setting are shown in Figure 9 and Table 1 respectively.

![Figure 8. Simulating Structure of Robot.](image)
Figure 9. Parameter settings.

Table 1. Parameters of Leg.

<table>
<thead>
<tr>
<th>Port</th>
<th>Coordinate Value (CM)</th>
<th>Port</th>
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<th>Coordinate Value (CM)</th>
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<td></td>
<td></td>
<td>CS3</td>
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<td></td>
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<tr>
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Table 2. Parameters of Arm.

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<td></td>
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Table 3. Parameters of Body.

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<tr>
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</table>
Table 4 shows the setting the time of the simulation and the steps according to the movement planning mentioned in this article.

<table>
<thead>
<tr>
<th></th>
<th>Height of gravity (m)</th>
<th>X direction (m)</th>
<th>Y direction (m)</th>
<th>Time (s)</th>
<th>Angle $\theta$ (°)</th>
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<td>10</td>
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<tr>
<td>Sideway</td>
<td>0.343</td>
<td>5</td>
<td>3</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Backward</td>
<td>0.343</td>
<td>5</td>
<td>3</td>
<td>10</td>
<td>60</td>
</tr>
</tbody>
</table>

The Figure 11 is the footprint sequence and the trajectory of the COM of the omnidirectional movement. At the beginning of the movement, in order to avoid falling down because of the physical inertia, the steps are relatively small. But after the fourth step, the robot walks at a constant speed. As soon as it finishes moving ahead, before sideway moving, the gait changes in a sudden and the robot begins reducing the speed. When the initial position of the sideway moving is set, the robot accelerates gradually to the constant speed. At this point, the robot completes the transition of the movement state successfully. After finishing the sideway moving and before the backward moving, the robot begins to reduce the speed again until it reaches the initial position of the backward moving. It moves a step backward and turns an angle. With every step backward, the supporting leg turns a certain angle. In this process, the speed of every step is the same except for the last two steps before finishing moving. The robot returns back to the beginning position. The whole process of the humanoid robot’s omnidirectional movement completes.

In the simulation process, the step sequence and the trajectory of the COM (Center of Mass) are connected. In the walking process, ZMP (Zero moment point) and the COM coincide. Through the observation the trajectory of the COM, it is concluded that the ZMP curve is in the stable area enclosed by the supporting legs.
Conclusions

The omnidirectional movement of the humanoid robot can be divided into several moving processes in every direction. Based on the three-dimensional linear inverted pendulum model, the moving process can be planned individually. The moving direction-switching transition method based on the segment interpolation is used in the transition of directions. In the future research, the focus will be on studying the trajectory flexibility and the energy consumption optimization of the omnidirectional movement of humanoid robots.

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(5) Guangdong Technology Innovative Special Fund for Undergraduate (Key Climbing Project): Study of Complicated Motion System of 17-DOF Humanoid Robot
(6) Innovation and Business Project for Undergraduate of Guangdong University of Petrochemical Technology: Study of Collaborative Negotiation and Task Allocation of Big Group Robots

References


