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Falling forward of humanoid robot based on similarity with parametric optimum

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Abstract. The designing method of falling-forward locomotion of humanoid robot based on the locomotion similarity is proposed. Firstly, the locomotion similarity is analyzed and synchronous transition for the key postures is proposed. Then, the kinetics constraint equations and the associated physical condition constraints for the 4-level headstand pendulum of robot's falling-forward locomotion under the condition of similarity transition are constituted. Finally, the method based on parametric control and the enhancing technique is adopted to optimize the parameters in the touching ground process of falling forward. The experiments showed the validity of this designing method.

Key words. humanoid robot, similarity, constraint, zero moment point (zmp), parametric optimum.

1. Introduction

Evolution gives human the extraordinary ability to control their muscles and perform different complex movements fluently without consuming much energy, which helps human survive in the changing environment [1]. Humanoid robot has a similar joint ratio with human, so making humanoid robot moving fluently like human does and low down the power consuming has become one of the hot research topics [2,3].

Many researchers have contributed lots of ideas about the locomotion similarity of humanoid robot, which can be summarized as two aspects. The first one is about the complex motion designing method, for example, applying human movements capturing and matching system to perform Tai Chi[4], generating characteristic symbols by separating human movements into basic motions and then use the symbols to instruct robot's movements[5], analyzing characteristics of stability and similarity of complex human movements then applying it to robot broadsword performance[6],

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extracting basic motions from human dancing movements and applying it to robot dancing performance[7], generating characteristic symbols of human movements and constructing database for humanoid robots[8], using mathematical techniques to analyze characteristics of human upper limb motions[9]. The second one is about the bipedal movement designing method, such as extracting key postures of human when they are walking or playing football and applying it to soccer robot by dynamic constraints[10], generating standard bipedal movement by using EDA (Estimation of distribution algorithm), optimizing robot bipedal moving instructions to better imitate human, designing a new bipedal moving mode and gait transit method, using cubic spline function to design a global optimum bipedal moving gait cycle and ensure every point of a joint has second derivative.

The locomotion similarity designs of the mentioned researches restrict robot's movement near its stable ZMP (Zero movement point), which means it could not be applied to the design of falling locomotion of humanoid robot. As humanoid robot has a high center of gravity and a small foot support, falling down is hard to avoid when it's moving. The falling-forward process can be describe as the robot transit from a stable ZMP range (standing) to an unstable ZMP range (falling) and finally reenter a stable ZMP range (hitting the ground).While hitting the ground, the locomotion of the robot can't be optimize using locomotion similarity method, which may increase the chance to damage the robot.

To solve that problem, a designing method of falling-forward locomotion of humanoid robot based on the locomotion similarity is proposed, the method based on parametric control and the enhancing technique is adopted to optimize the parameters in the hitting ground process of falling forward to ensure an optimal stability and the least impact.

2. Locomotion similarity transition of falling forward

2.1. Analyzing the locomotion similarity

Suppose $p^{\mathrm{H}} = \left\{\Phi^{\mathrm{H}}(0), ..., \Phi^{\mathrm{H}}(t), ..., \Phi^{\mathrm{H}}(\mathrm{T})\right\}$ are all discrete key postures when a human is falling forward during time period $[0, T]$, where

$\Phi^{\mathrm{H}}(t) = \left\{\varphi_1^{\mathrm{H}}(t), ..., \varphi_i^{\mathrm{H}}(t), ..., \varphi_N^{\mathrm{H}}(t)\right\}^{\mathrm{T}}$ are angles of each joint in moment t and $N$is the number of joints. Correspondingly, $p^{\mathrm{R}} = \left\{\Phi^{\mathrm{R}}(0), ..., \Phi^{\mathrm{R}}(t), ..., \Phi^{\mathrm{R}}(\mathrm{T})\right\}$ are all discrete key postures of a robot and $\Phi^{\mathrm{R}}(t) = [\varphi_1^{\mathrm{R}}(t), \ldots, \varphi_i^{\mathrm{R}}(t), \ldots, \varphi_N^{\mathrm{R}}(t)]^{\mathrm{T}}$ are angles of each joint as well. Then the similarity can be defined as:

$$S_i^{\mathrm{H}\sim\mathrm{R}}(t) = \tau \cdot \left(1 + \frac{|\varphi_i^{\mathrm{R}}(t) - \varphi_i^{\mathrm{H}}(t)|}{\varphi_{i\_\max}^{\mathrm{R}} - \varphi_{i\_\min}^{\mathrm{R}}}\right)^{-1} + (1-\tau) \cdot \left(1 + \frac{|\dot{\varphi}_i^{\mathrm{R}}(t) - \dot{\varphi}_i^{\mathrm{H}}(t)|}{\dot{\varphi}_{i\_\max}^{\mathrm{R}} - \dot{\varphi}_{i\_\min}^{\mathrm{R}}}\right)^{-1}$$

$$S^{\mathrm{H}\sim\mathrm{R}}(t) = \frac{\sum_{n=1}^{N} S_i^{\mathrm{H}\sim\mathrm{R}}(t)}{N}$$

$$S^{\mathrm{H}\sim\mathrm{R}} = \frac{\int_{t=0}^{T} S^{\mathrm{H}\sim\mathrm{R}}(t)dt}{T}$$

Where $\varphi_{i\_\max}^{\mathrm{R}} \varphi_{i\_\min}^{\mathrm{R}}$ are the maximum and minimum in the slew range of the i^{th} joint. Equation (1) shows the similarity between the ithjoint of robot and the ithjoint of human in moment t, where $\tau$is the transform coefficient lying between 0 and 1. τ approaches to 1 indicates the movement is tend to be static and conversely, τ approaches to 0 indicates the movement is tend to transit rapidly. Equation (2)shows the average similarity of all joints in moment t and equation (3) shows the average similarity in the time period T. Apparently S lies between 0 and 1, S closer to1, indicates higher similarity.

2.2. Transiting the locomotion similarity

As the body structure and proportion of robot is different form those of human, the data of human's falling forward movement can't be directly used to design the robot's locomotion, therefore, key postures need to be extracted from the trajectory to analyze characteristics of human falling forward movement. Basic on the principle of key postures extracting[6,16,17], the standing posture before falling and the posture after falling are chosen to be key postures as they are the initial posture and the terminal posture, transitional movement between them are consider to be basic sub phases.

When the robot is falling forward, key postures transfer in moment t is:

$$\varphi_i^{\mathrm{R}}(t) = \gamma\varphi_i^{\mathrm{H}}(t) + \Delta\varphi_i(t)$$

where γ is the transition degree lying between 0 and 1, $\Delta\varphi_i(t)$ is the convert angle composition. $\gamma \to 1$ and $\Delta\varphi_i(t) \to 0$ indicate the change of robot joints angles is more similar to those of human joints.

The transition between moment t and $t + \Delta t$ is:

$$\begin{cases} \varphi_i^{\mathrm{R}}(t+\Delta t) = \varphi_i^{\mathrm{R}}(t) + \Delta\varphi_i^{\mathrm{R}} \\ \dot{\varphi}_i^{\mathrm{R}}(t+\Delta t) = \dot{\varphi}_i^{\mathrm{R}}(t) + \Delta\dot{\varphi}_i^{\mathrm{R}} \\ \ddot{\varphi}_i^{\mathrm{R}}(t+\Delta t) = \ddot{\varphi}_i^{\mathrm{R}}(t) + \Delta\ddot{\varphi}_i^{\mathrm{R}} \end{cases}$$

where $\Delta\varphi_i^{\mathrm{R}}$,$\Delta\dot{\varphi}_i^{\mathrm{R}}$,$\Delta\ddot{\varphi}_i^{\mathrm{R}}$ are changes of angle, angular speed and angular acceleration in time period Δt.

To show the coordination of locomotion, some of the robot's joints need to reach its target angle φ_i^R at the same time:

$$\varphi_{\mathrm{i}}^{\mathrm{R}}(t+\Delta t) = \varphi_i^{\mathrm{R}}(t) + \int_t^{t+\Delta t} \dot{\varphi}_i^{\mathrm{R}}(t)\mathrm{d}t = \varphi_i^{\mathrm{R}}(t) + \int_t^{t+\Delta t}\int_t^{t+\Delta t} \ddot{\varphi}_i^{R}(t)\mathrm{d}t\mathrm{d}t$$

after the transition, the key postures are $\varphi_i^{\mathrm{R}}(t) \in \Phi^{\mathrm{R}}$, $\varphi_i^{\mathrm{R}}(t+\Delta t) \in \Phi^{\mathrm{R}}$, which indicate:

$$\ddot{\varphi}_i^{\mathrm{R}}(t) = \frac{\mathrm{d}^2(\varphi_i^{\mathrm{R}}(t+\Delta t) - \varphi_i^{\mathrm{R}}(t))}{\mathrm{d}t^2}$$

$\ddot{\varphi}_i^{\mathrm{R}}(t) < 0$ indicates a deceleration movement, $\ddot{\varphi}_i^{\mathrm{R}}(t) = 0$ indicates a uniform movement and $\ddot{\varphi}_i^{\mathrm{R}}(t) > 0$ indicates an acceleration movement, therefore, by modifying $\ddot{\varphi}_i^{\mathrm{R}}(t)$ of each joint, key postures can synchronize.

3. Kinematics constraints and practical physical constraints

As the body structure and proportion of robot is different form those of human, only after correct the impacts of kinematics constraints and practical physical constraints, can the extracted parameters be applied to control robot.

3.1. Kinematics constraints

Fig. 1. process of falling forward

To transform locomotion more conveniently, the falling forward process is observe from side [Fig.1]. State A is the standing posture before robot falling forward while state B is the intermediate process of falling, state C is the stable posture after the falling. Mass of each connecting bar is m_1, m_2, m_3, m_4,the coordinate of ankle, knee, waist joint, shoulder, wrist is S_a, S_n, S_w, S_s, S_h. Suppose $\theta^{R}(t) = [\theta_1^{R}(t), \ldots, \theta_4^{R}(t)]^{T}$, $\theta_1^{R}(t)$,$\theta_2^{R}(t)$,$\theta_3^{R}(t)$,$\theta_4^{R}(t)$are angles between connecting bars and the vertical line and $\phi^{\mathrm{R}}(t) = [\phi_1^{\mathrm{R}}(t), \ldots, \phi_4^{\mathrm{R}}(t)]^{\mathrm{T}}$, $\phi_1^{\mathrm{R}}(t)$, $\phi_2^{\mathrm{R}}(t)$, $\phi_3^{\mathrm{R}}(t)$, $\phi_4^{\mathrm{R}}(t)$ are angles between each connecting bar.

State A: robot is standing

$S_{\mathrm{a}}^{\mathrm{A}} = [0\ 0\ 0]^{\mathrm{T}}$ $S_{\mathrm{n}}^{\mathrm{A}} = [0\ y_{\mathrm{n}}^{\mathrm{A}}\ z_{\mathrm{n}}^{\mathrm{A}}]^{\mathrm{T}}$ $S_{\mathrm{w}}^{\mathrm{A}} = [0\ y_{\mathrm{w}}^{\mathrm{A}}\ z_{\mathrm{w}}^{\mathrm{A}}]^{\mathrm{T}}$ $S_{\mathrm{s}}^{\mathrm{A}} = [0\ y_{\mathrm{s}}^{\mathrm{A}}\ z_{\mathrm{s}}^{\mathrm{A}}]^{\mathrm{T}}$ $S_{\mathrm{h}}^{\mathrm{A}} = [0\ y_{\mathrm{h}}^{\mathrm{A}}\ z_{\mathrm{h}}^{\mathrm{A}}]^{\mathrm{T}}$

$$F(S_{\mathrm{a}}^{\mathrm{A}}) \cdot e_z \equiv 0$$

$$0 < F(S_n^{\mathrm{A}}) \cdot e_z < F(S_w^{\mathrm{A}}) \cdot e_z < F(S_s^{\mathrm{A}}) \cdot e_z$$

$$V^{\mathrm{A}} \equiv v(\phi(\mathrm{A}), \dot{\phi}(\mathrm{A}), \theta(\mathrm{A}), \dot{\theta}(\mathrm{A})) = \frac{\partial^2 C(\phi(\mathrm{A}), \theta(\mathrm{A}))}{\partial\phi\partial\theta} \dot{\phi}(\mathrm{A})\dot{\theta}(\mathrm{A}) = \ [0\ k_{\mathrm{y}}^{\mathrm{A}}\ k_{\mathrm{z}}^{\mathrm{A}}]$$

Where $C(\phi(\mathrm{A}), \theta(\mathrm{A}))$ is the initial coordination of robot, $F(S_{\mathrm{a}}^{\mathrm{A}}) \cdot e_z$ is high of ankle, V^{A} is speed in state A, $\phi(\mathrm{A})$,$\theta(\mathrm{A})$,$\dot{\phi}(\mathrm{A})$,$\dot{\theta}(\mathrm{A})$ are angles and angular speed of joints in state A, $k_{\mathrm{y}}^{\mathrm{A}}$,$k_{\mathrm{z}}^{\mathrm{A}}$ are speed in y and z axis, $k_{\mathrm{y}}^{\mathrm{A}} \geq 0 k_{\mathrm{z}}^{\mathrm{A}} \geq 0$.

State B: In falling forward process (the first sub phase), position of robot's ankles remain while its upper limb rotate around its ankle and falling forward.

$S_{\mathrm{a}}^{\mathrm{B}} = [0\ 0\ 0]^{\mathrm{T}}$ $S_{\mathrm{n}}^{\mathrm{B}} = [0\ y_{\mathrm{n}}^{\mathrm{B}}\ z_{\mathrm{n}}^{\mathrm{B}}]^{\mathrm{T}}$ $S_{\mathrm{w}}^{\mathrm{B}} = [0\ y_{\mathrm{w}}^{\mathrm{B}}\ z_{\mathrm{w}}^{\mathrm{B}}]^{\mathrm{T}}$ $S_{\mathrm{s}}^{\mathrm{B}} = [0\ y_{\mathrm{s}}^{\mathrm{B}}\ z_{\mathrm{s}}^{\mathrm{B}}]^{\mathrm{T}}$ $S_{\mathrm{h}}^{\mathrm{B}} = [0\ y_{\mathrm{h}}^{\mathrm{B}}\ z_{\mathrm{h}}^{\mathrm{B}}]^{\mathrm{T}}$

$F(S_{\mathrm{a}}^{\mathrm{B}}) \cdot e_z \equiv 0 F(S_{\mathrm{n}}^{\mathrm{B}}) \cdot e_z > 0 F(S_{\mathrm{w}}^{\mathrm{B}}) \cdot e_z > 0 F(S_{\mathrm{s}}^{\mathrm{B}}) \cdot e_z > 0 F(S_{\mathrm{h}}^{\mathrm{B}}) \cdot e_z > 0$

Where $k_{\mathrm{y}}^{\mathrm{B}} > 0$ and $k_{\mathrm{z}}^{\mathrm{B}} > 0$.

$$V^{\mathrm{B}} \equiv v(\phi(\mathrm{B}), \dot{\phi}(\mathrm{B}), \theta(\mathrm{B}), \dot{\theta}(\mathrm{B})) = \frac{\partial^2 C(\phi(\mathrm{B}), \theta(\mathrm{B}))}{\partial\phi\partial\theta} \dot{\phi}(\mathrm{B})\dot{\theta}(\mathrm{B}) = \ [0\ k_{\mathrm{y}}^{\mathrm{B}}\ k_{\mathrm{z}}^{\mathrm{B}}]$$

Where $k_{\mathrm{y}}^{\mathrm{B}} > 0$ and $k_{\mathrm{z}}^{\mathrm{B}} > 0$.

State C: knee and wrist of the robot hit the ground

$S_{\mathrm{a}}^{\mathrm{C}} = [0\ 0\ 0]^{\mathrm{T}}$ $S_{\mathrm{n}}^{\mathrm{C}} = [0\ y_{\mathrm{n}}^{\mathrm{C}}\ 0]^{\mathrm{T}}$ $S_{\mathrm{w}}^{\mathrm{C}} = [0\ y_{\mathrm{w}}^{\mathrm{C}}\ z_{\mathrm{w}}^{\mathrm{C}}]^{\mathrm{T}}$ $S_{\mathrm{s}}^{\mathrm{C}} = [0\ y_{\mathrm{s}}^{\mathrm{C}}\ z_{\mathrm{s}}^{\mathrm{C}}]^{\mathrm{T}}$ $S_{\mathrm{h}}^{\mathrm{C}} = [0\ y_{\mathrm{h}}^{\mathrm{C}}\ 0]^{\mathrm{T}}$

$F(S_{\mathrm{a}}^{\mathrm{C}}) \cdot e_z \equiv 0$ $F(S_{\mathrm{n}}^{\mathrm{C}}) \cdot e_z \equiv 0$ $F(S_{\mathrm{h}}^{\mathrm{C}}) \cdot e_z \equiv 0$

$F(S_{\mathrm{w}}^{\mathrm{C}}) \cdot e_{\mathrm{z}} > 0$ $F(S_{\mathrm{s}}^{\mathrm{C}}) \cdot e_{\mathrm{z}} > 0$

$$V^{\mathrm{C}} \equiv v(\phi(\mathrm{C}), \dot{\phi}(\mathrm{C}), \theta(\mathrm{C}), \dot{\theta}(\mathrm{C})) = \frac{\partial^2 C(\phi(\mathrm{C}), \theta(\mathrm{C}))}{\partial\phi\partial\theta} \dot{\phi}(\mathrm{C})\dot{\theta}(\mathrm{C}) = \ 0$$

3.2. Practical physical constraints

3.2.1. Joint angle constraints To avoid collision of joints, distance between two limbs need to meet equation

$D(i,j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \geq 0$

At the same time, angle of each joint need to meet equation (**??**)[8]:

$L(\phi^{\mathrm{R}}(t)) = \sum_{i=1}^{N} \exp(-\mu(\phi_i^{\mathrm{R}} - \phi_{i\_\mathrm{min}}^{\mathrm{R}})\phi_{i\_\mathrm{max}}^{\mathrm{R}} - \phi_{i\_\mathrm{min}}^{\mathrm{R}}) + \exp(-\mu(\phi_{i\_\mathrm{max}}^{\mathrm{R}} - \phi_i^{\mathrm{R}})\phi_{i\_\mathrm{max}}^{\mathrm{R}} - \phi_{i\_\mathrm{min}}^{\mathrm{R}})$

Where μ is the adjustment coefficient lying between 0 and 1.

3.2.2. Expanded ZMP zero moment point constraints When falling forward, robot leave the stable ZMP range formed by its feet and enter an unstable state, after hitting the ground it reenter a stable ZMP range formed by its hands and feet. Suppose $(x^{\mathrm{zmp}}, y^{\mathrm{zmp}})$ is coordination of the ZMP:

$$(x^{\mathrm{zmp}}, y^{\mathrm{zmp}}) = \left(\frac{\sum_{i=1}^{N}[m_i(\ddot{z}_i+g)x_i - m_i\ddot{x}_i z_i - I_{iy}\dot{\mathrm{K}}_{iy}]}{\sum_{i=1}^{N} m_i(\ddot{z}_i+g)}, \frac{\sum_{i=1}^{N}[m_i(\ddot{z}_i+g)y_i - m_i\ddot{y}_i z_i - I_{ix}\dot{\mathrm{K}}_{ix}]}{\sum_{i=1}^{N} m_i(\ddot{z}_i+g)} \right)$$

Where m_i is mass of the i^{th}connecting bar, (x_i, y_i, z_i) is coordination of the center of mass of i^{th}connecting bar, $g$is acceleration of gravity, $I$is the moment of inertia of the round connecting bar, $\dot{\mathrm{K}}$is absolute acceleration component of the center of mass of i^{th}connecting bar.

After falling forward, the new range of ZMP can be described as:

$$C^{\mathrm{ZMP}_{\mathrm{COM}}}(t) = \begin{cases} left\_\max_x^{\mathrm{zmp}}(t) \le x^{\mathrm{zmp}} \le right\_\max_x^{\mathrm{zmp}}(t) \\ left\_\max_y^{\mathrm{zmp}}(t) \le y^{\mathrm{zmp}} \le right\_\max_y^{\mathrm{zmp}}(t) \end{cases}$$

Where $left\_\max_x^{\mathrm{zmp}}(t)$,$right\_\max_x^{\mathrm{zmp}}(t)$,$left\_\max_y^{\mathrm{zmp}}(t)$,$right\_\max_y^{\mathrm{zmp}}(t)$ is the max range in axis X and Y.

4. Parametric optimization of falling forward when touching ground

After correcting the impacts of kinematics constraints and practical physical constraints, the extracted parameters can be applied to control robot, however, to gain an optimal stability and the least impact, the method based on parametric control and the enhancing technique needs to be adopted to optimize the parameters in the hitting ground process of falling forward. The method uses piecewise constant to approach the optimal solution, meanwhile, a strengthening technology is adopted to transform the directive of index function in the original moment to the directive of the wanted parameter in new moment, solves the high dimensional complex nonlinear optimization problem efficiently [18-20].

The unbalance torque will increase the angular momentum of the robot, if the angular momentum is the least at the moment of hitting ground, the robot will get least impact. Suppose the momentum of the ith headstand pendulum at the hitting ground moment is i, where i is the speed of the ith headstand pendulum, the sum of momentum is i, the instantaneous angular momentum is:

By finishing all of the mentioned steps, a set of approximate solutions of parameters for the optimum controlling problem of robot falling forward process can be solve, which can minimum the angular momentum when hitting the ground and greatly reduce the impact.

5. Experiments and results

The experiments are based on the humanoid robot Nao produced by Aldebaran, which height 58cm and weight 4.3kg. The robot has 25 degrees of freedom, including 2*5 for arms (2 for shoulder, 1 for upper arm, 1 for elbow, 1 for wrist), 1 for waist, 2*6 for legs (3 for hip, 1 for knee, 2 for ankle), 2 for head.

Figure 2 shows the falling forward process of human, sampling time is 100 ms and the initial speed is 100/s

The changes of parametric controlled variables over time is shown in Fig.3, Fig.4 compares PR-S and GA (Genetic algorithm, 9 initial populations, 11 dimensions, the mutation probability is 0.7%, the number of iterations is 500). It's clear that

Fig. 2. Falling forward process of humanFalling forward process of human

PR-S approaches optimum after 250 steps while GA approaches after 350 steps.

Fig.5 and Fig.6 show the simulation movement and real movement of the robot after optimization using parametric optimum. Fig.7 compares tracks of robot's right joints angles and those of human when falling forward, apparently, the track of human is smooth and continuous while due to the mechanical structure of robot, the track of robot is has some steps.

6. Summary

In this article, the falling-forward locomotion of humanoid robot is analyzed based on the locomotion similarity. Key postures transform approach considering kinetics constraints and the physical constraints are proposed. At the same time, the method based on parametric control and the enhancing technique is adopted to

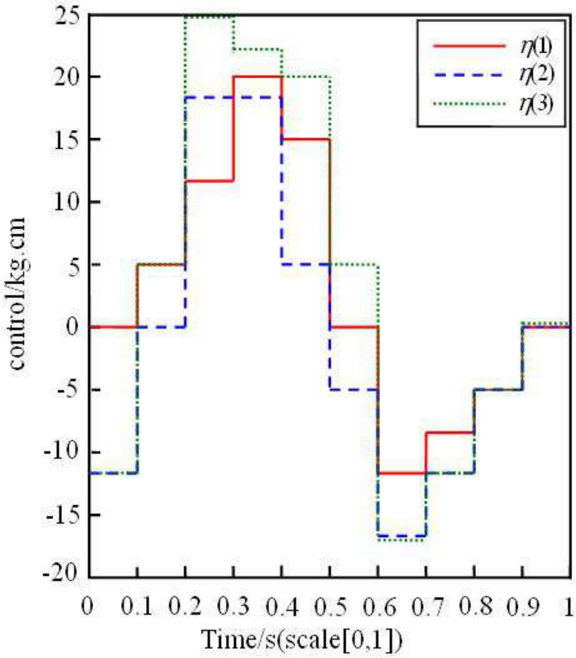

Fig. 3. controlling variables with time

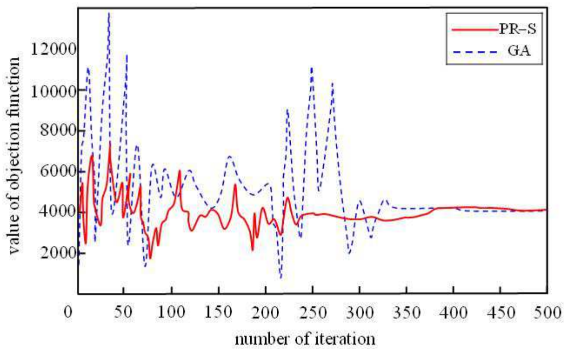

Fig. 4. Convergences of PR-S and GA

optimize the parameters in the touching ground process of falling forward, ensuring an optimal stability and the least impact.

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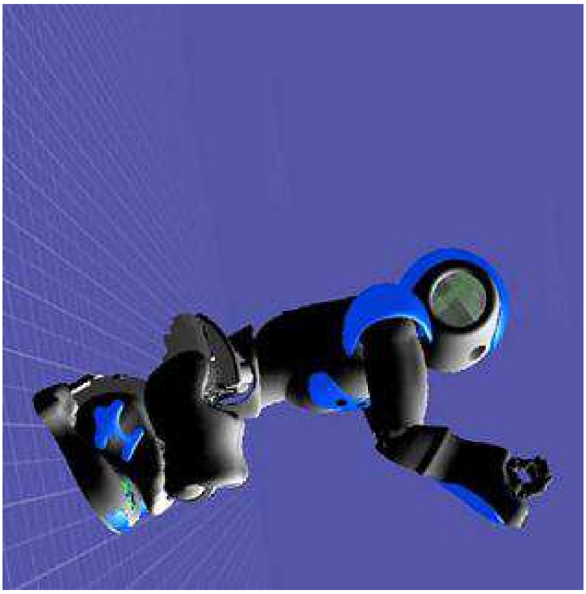

Fig. 5. Simulating effects of falling-forward actions

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Fig. 6. Practical effects of falling-forward process

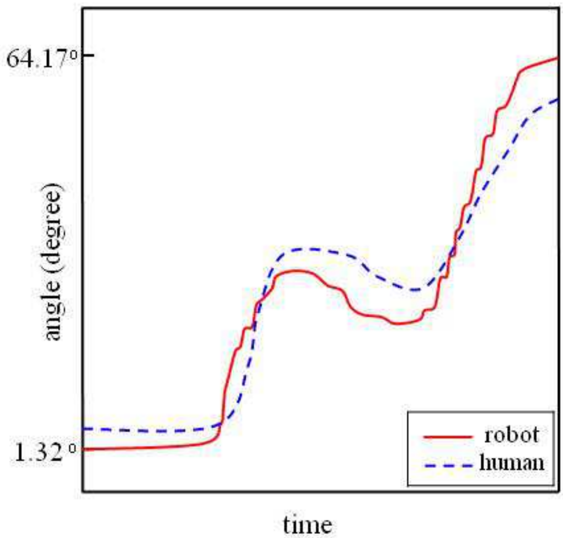

Fig. 7. Angel varieties of robot's joints when falling forward