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Motion Suspension System for Humanoids in case of Emergency

- Real-time Motion Generation and Judgment to suspend Humanoid -

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Abstract

This paper presents a motion suspension system to suspend humanoid motion in case of emergency. Once humanoids start their motions in human daily environments, there is a possibility that humanoids will meet with several emergencies such as hurting humans and injuring themselves. Even so, humanoids should be controlled so that they avert such emergencies in real-time. To realize this demand, we propose a method of real-time judgment of emergency prediction by humanoids. We also propose a simple and effective method of real-time pattern generation to force humanoids to stop immediately by one step without falling. To verify the validity of the proposed method, we finally present experimental results using a humanoid robot HRP-2, which include experiments at 2.8 [km/h] walks.

1. Introduction

The needs for robots have recently been changed from factory automation to human friendly robot system. Coming increasingly aging societies, robots that assist human activities in human daily environments such as in offices, homes and hospitals are expected. Especially, emergence of humanoid robots is strongly expected because of anthropomorphism, friendly design, applicability of locomotion, behavior within the human living environments, and so on.

Back to the field of robotics researches, a research on biped humanoids is currently one of the most exciting topics. It is no exaggeration to say that the great success of HONDA humanoid robot makes the current research on the world's humanoid robot to become very active area [1-3]. Since the second prototype HONDA humanoid robot: P2 was revealed in 1996, many biped humanoid robots have been developed [4-13]. For instance, ASIMO [3], QRIO [8], and HRP-2 [10] demonstrated their performances at the robot exhibition: ROBODEX2003. JOHNNIE [12] and HUBO [13] also did at the Hannover Fair 2003 and the Wired NextFest 2005, respectively. However, those performances are still played in environments that are separated from the sphere of human lives and activities.

Once humanoids, which coexist with humans in human daily environments, such as in offices, homes and factories, start their motions, there is a possibility that humanoids will meet with several emergencies. For example, a human does not always keep space from humanoids and may get into operational space of humanoids against his/her will. In such a case, humanoids may hurt to humans. Otherwise, it is possible that humanoids will fall over to the ground by contact with humans and will be damaged. Another example of emergencies is that humanoids don't a little have hardware troubles in operation, such as breaking of wire and sensor trouble. Since humanoids are not fixed on the ground, humanoids may be injured in the fall. Excessively unexpected slippery floor and irregular floor also bring an emergency to humanoids. Even if humanoids unexpectedly meet with such emergencies shown in Figure 1, humanoids should be controlled so that they avert such emergencies in real-time.

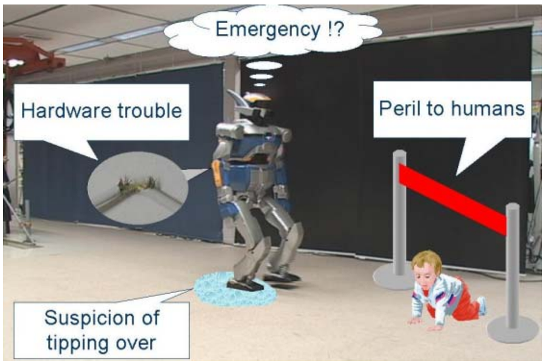

Figure 1. Emergencies of Humanoid

To realize this demand, we propose a method of real-time judgment of emergency prediction by humanoids. We also

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propose a method of real-time pattern generation to force motions of humanoid to stop immediately by one step without falling. Although we had already proposed the other method of suspension motion generation in [14], the proposed method in this paper is different from that, and is so simpler than that. Finally, we present experimental results using a humanoid robot HRP-2, which include experiments at 2.8 [km/h] walks, to verify the validity of the proposed method.

2. Relevant Works

The research presented in this paper has a relevant to researches on a real-time pattern modification according as sensor information and a real-time pattern generation.

Up to now, several methods of real-time pattern modification according as sensor information have been proposed. Hirose proposed the walk stabilization based on ground reaction force control, desired ZMP control, and foot landing position control [3]. We also developed the walk stabilizer with function of slip detection [15]. These stabilizers increase stability of biped humanoid robots on the real environments and are effective for replaying given patterns stably. However, they have neither a function of emergency prediction nor that of pattern generation for emergency suspension.

Several researches that focus on real-time walking pattern generation have been studied recently. Kajita proposed a real-time pattern generator that is conducted by analyzing the dynamics of a three-dimensional inverted pendulum mode [16]. Although this method generated a stable gait by changing foot placements from the original assignment, it was not applicable to a situation like a walking on stepping-stones where the foot must be placed on the specified location. To overcome this problem, Kajita also proposed a method of walking pattern generation by using a preview control of the zero moment point (ZMP) [17]. However, since these methods consume preparatory times to generate stop motions, they require more than two steps to stop motions. Namely they are insufficient for responding to emergencies. Nishiwaki proposed an online method of a walking pattern generation of humanoid by updating and connecting subsequent motion patterns to the old ones [18]. To apply this method to emergency suspension, we have to prepare so many subsequent motion patterns that should be as short as possible. Sugihara proposed a fast online gait planning method with boundary condition relaxation [19]. In this method, since it is assumed that the moment around the center of gravity (COG) is ignored for fast calculations at planning, the effect of assumption appears as the error between the planned ZMP and the obtained ZMP. This error is regrettably undesirable for our control system. Morisawa proposed a method to generate emergency stop motions by using analytical solutions of COG dynamics [14]. Although this method certainly provides stop motions within one step, this method requires the computational costs because of complicated algorithm. Implementing two pattern generators that are a general one such as [16] and an emergency one such as [14], sampling time of control system is oppressed.

This paper therefore proposes the suspension motion system consisting both of judgment of emergency and suspension motion generator with simple algorithm. The proposed method of suspension motion generator is based on a pattern modification rather than a pattern generation as follows.

3. Balance Control System

3.1. Previous Control System

Before introducing our new balance control system with proposed motion suspension system in Section 3.2., we indicate an issue of our previous balance control system in this Section 3.1. Figure 2 shows the previous balance control system that had been employed in HRP-2. This control system mainly consists of “Pattern Generator,” “Stabilizer,” “Joint Servo,” and “Operator Terminal.”

Through “Operator Terminal” shown in lower-left of Figure 2, we send several commands to “Pattern Generator” for making HRP-2 start motions.

Our “Pattern Generator” shown in top-left of Figure 2 dynamically provides both online stable motion patterns for HRP-2 and offline ones. This pattern generator is constructed using the preview control of ZMP [17]. Output signals from this pattern generator are reference of joint angles, reference of ZMP, and so on. In the previous balance control system, these output signals from “Pattern Generator” are inputted into “Stabilizer.”

“Stabilizer” shown in top-middle of Figure 2 provides a command of joint angles to increase stability of HRP-2 on the real environments. To realize that, “Stabilizer” utilizes almost of all information used in the balance control system of HRP-2, namely output signals from “Pattern Generator” and sensor signals such as joint angles, force/torque in the foot and in the wrist, acceleration of body, and angular velocity of body, as input signals. Based on these input signals, “Stabilizer” modifies the reference of joint angles generated by “Pattern Generator” so that HRP-2 can cope with permissible unexpected slippery floor and irregular floor. This modified reference of joint angles is outputted from “Stabilizer” into “Joint Servo” as a command of joint angles.

“Joint Servo” shown in top-rather-right of Figure 2 faithfully replays a command of joint angles by using feedback signal of joint angles. Here, the command of joint angles is made from modifying the reference of joint angles generated by “Pattern Generator” in “Stabilizer.” The sampling rate of “Joint Servo” is 1.0 [msec] on ART-Linux [20] that enables the execution of real-time processes at user level.

By using this previous balance controller, the stable motions including dances can be achieved [21]. However, this balance controller has still several issues to be improved. One of them is that this controller can’t make HRP-2 stop immediately. Since this controller is rather a playback controller as far as motions given by “Pattern Generator” are concerned, this controller can’t cope with emergencies.

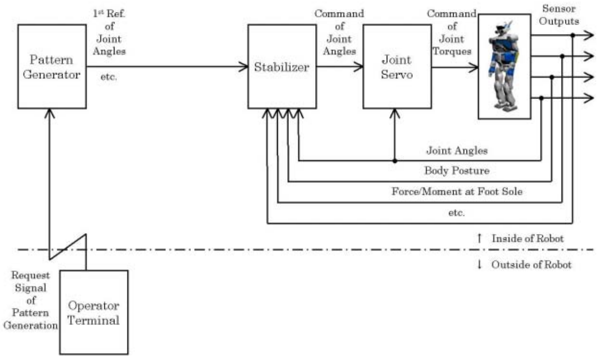


Figure 2. Previous Control System
that can’t cope with Emergency

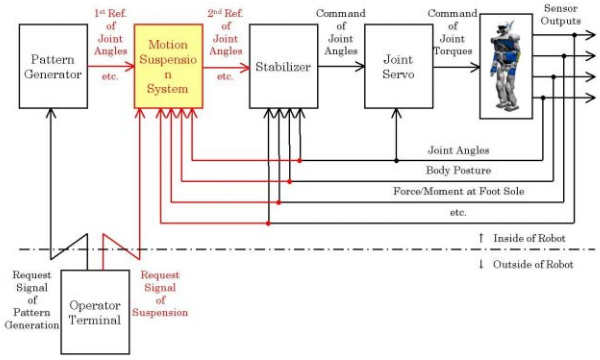


Figure 3. Proposed Control System with Motion Suspension System
that can cope with Emergency

3.2. New Control System

To overcome the issue indicated in Section 3.1, the motion suspension system, which is newly presented in this paper, is additionally implemented into the previous control system. Figure 3 shows a new balance control system that is currently employed in HRP-2. Here, the red block and red lines are the proposed “Motion Suspension System” and input/output signals of “Motion Suspension System.” As shown in Figure 3, “Motion Suspension System” is arranged between “Pattern Generator” and “Stabilizer.”

Figure 4 shows the detail of “Motion Suspension System.” “Motion Suspension System” consists of a process portion of “Judge of Suspension” and that of “Suspension Motion Generator.” Although the detail of each process will be explained in the next chapter, its overview is as follows.

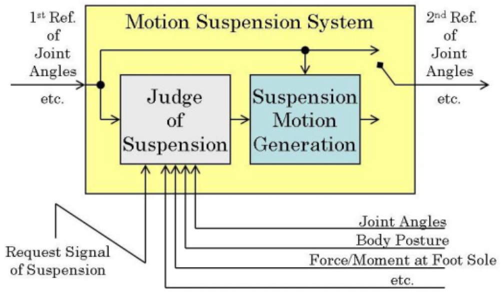


Figure 4. Motion Suspension System

The process portion of “Judge of Suspension” judges in real-time whether HRP-2 should be suspended immediately or not to prevent emergency accidents. If this process judges no, “Motion Suspension System” just hands over the original references given by “Pattern Generator” to “Stabilizer.” Namely, HRP-2 keeps playing original motions. If yes, this process requests the process portion of “Suspension Motion Generator” to start processing.

The process portion of “Suspension Motion Generator” starts to generate suspension motions that are connected with the original motions at the time when this process receives a request from “Judge of Suspension.” At the same time, this process switches over the output signals of “Motion Suspension System” so that “Stabilizer” can receive the references generated by this process. As a result, HRP-2 smoothly starts to play the suspension motions when “Judge of Suspension” judges that HRP-2 should be stopped immediately.

4. Motion Suspension System

In this section, the details of proposed “Motion Suspension System” are explained, while its overview is briefly explained in Section 3.2. The rest of this section is organized as follows. In Section 4.1, the method of real-time judgment of emergency prediction is explained by using one example. In Section 4.2, we consider an acceptable period for starting suspension that leads a realization both of simply generating suspension motions. The method of real-time pattern generation that forces humanoid motions to stop immediately by one step without falling is explained in Section 4.3.

4.1. Judge of Suspension

“Judge of Suspension” is processed in real-time based on several sensors mounted on HRP-2, references from “Pattern Generator,” and a request signal from “Operator Terminal.”

When the request signal of suspension is send to “Motion Suspension System” from “Operator Terminal,” this process judges that HRP-2 should be suspended immediately. Moreover, this process also judges the necessity of suspension when emergency information that can cause HRP-2 tipping over is detected. The latter judgment is explained in detail as follows.

Now, let us introduce one example to explain how to detect emergency information in “Judge of Suspension.” Figure 5 shows a time chart concerning the judgment of suspension at using body posture information.

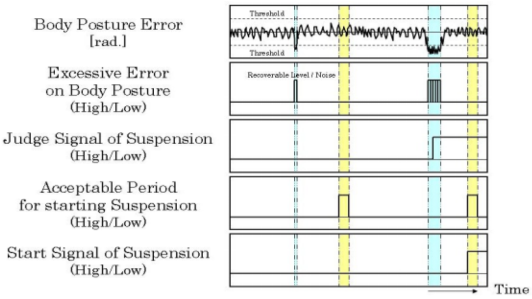


Figure 5. Time Chart concerning “Judge of Suspension”

The first upper block shown in Figure 5 gives us a body posture error that is derived by subtracting a real angle of body posture from a reference one. Here, the real angle of body posture is calculated in our implemented “Kalman Filter” by using 3-axes angular velocity sensor and 3-axes acceleration sensor. The reference angle of body posture is given from “Pattern Generator.”

The second upper block shown in Figure 5 indicates a signal of excessive error on body posture. When the body posture error is over/under threshold, this signal, *Eflag_φ*, becomes high/low as following equations.

$$\varphi_{err} = [\,(\varphi_r^{\,ref} - \varphi_r)^2 + (\varphi_p^{\,ref} - \varphi_p)^2\,]^{1/2} \tag{1}$$

$$Eflag\_\varphi \;=\; \begin{cases} 1 & (\text{ at } \quad \varphi_{err} \geq \varphi_{threshold}\,) \\ 0 & (\text{ at } \quad \varphi_{err} < \varphi_{threshold}\,) \end{cases} \tag{2}$$

Here, φ_{err} , φ_r , φ_p , and $\varphi_{threshold}$, represent the body posture error, the real angle of roll-axis body posture, the real angle of pitch-axis one, and a threshold angle, respectively. The subscript ref denotes reference value.

The signal of excessive error on body posture, *Eflag_φ*, will be high in case any emergencies, such as an unstable motion caused by any disturbance, trouble with 3-axes angular velocity sensor and/or 3-axes acceleration sensor, and disconnection between sensor and main computer. By observing this signal, *Eflag_φ*, we can predict a possibility of emergencies that can cause HRP-2 tipping over, while we don’t inquire into the reason why this signal, *Eflag_φ*, is high.

The third upper block shown in Figure 5 expresses a judge signal of suspension, *Jflag_φ*. The status of this signal, *Jflag_φ*, is high or low, and is decided from an accumulative judgment based on the signal of excessive errors, as follows.

$$count\_\varphi_{err} \begin{cases} += \;\; 1 & (\text{ at } \quad Eflag\_\varphi = 1\,) \\ -= \;\; 1 & (\text{ at } \quad Eflag\_\varphi = 0\,) \end{cases} \tag{3-1}$$

$$\text{whereas} \qquad 0 \leq count\_\varphi_{err} \leq count\_\varphi_{max} \tag{3-2}$$

$$Jflag\_\varphi \;=\; \begin{cases} 1 & (\text{ once } \quad count\_\varphi_{err} = count\_\varphi_{max}\,) \\ 0 & (\text{ never } \quad count\_\varphi_{err} = count\_\varphi_{max}\,) \end{cases} \tag{4}$$

Here, $count\_\varphi_{err}$ and $count\_\varphi_{max}$ represent a counter for accumulative judgment of suspension and its maximum value, respectively.

By using the accumulative judgment given in Equation (3), we evade misjudgments of suspension caused by sensor noise. Equation (3) also provides us with ignoring the case of recoverable posture errors.

Equation (4) tells us that the judge signal of suspension, *Jflag_φ*, whose initial is low, becomes high, once the process of “Judge of Suspension” predicts a possibility of emergencies. Due to safety first, the judge signal of suspension, *Jflag_φ*, isn’t reset at zero, once *Jflag_φ* is high. Even if the status of this signal, *Jflag_φ*, becomes high, the “Judge of Suspension” doesn’t yet request the process portion of “Suspension Motion Generator” to start processing. The reason will be explained in Section 4.2.

Using the same technique obtaining the judge signal of suspension, *Jflag_φ*, the “Judge of Suspension” processes other suspension judgments. For example, outputs from foot force/moment sensor, slip information calculated by the slip-observer [15], error signals from servo drivers, the request signal from “Operator Terminal,” and etc. are used for suspension judgments in our system.

4.2. Start Time for Simple Suspension

It is desirable that the suspension motions are started at any state of robot. However, we think it’s not indispensable that the generation of suspension motions is started at any state of current humanoid because of the followings.

One of reasons is that suspension motions would be finished at double support condition, even if generation of suspension motions starts at single support phase. Since an area of support polygon of double support condition is larger than that of single support condition, suspension motions at double support condition are suitable for stability. Another reason is that it’s not too late to start generating suspension motions at double support phase, since walking speed of current humanoid is not so first compared with humans. The computational costs for generating suspension motions are also one of reasons. To reduce them, it is wiser to modify the original patterns given by “Pattern Generator,” compared with preparing a second pattern generator that is specialized for suspension such as [14].

Due to the reasons above, this paper then employs the following ideas to generate suspension motions simply.

Basic Idea I :

The generation of suspension motions is started at double support phase. And then suspension motions are finished at double support condition.

Basic Idea II :

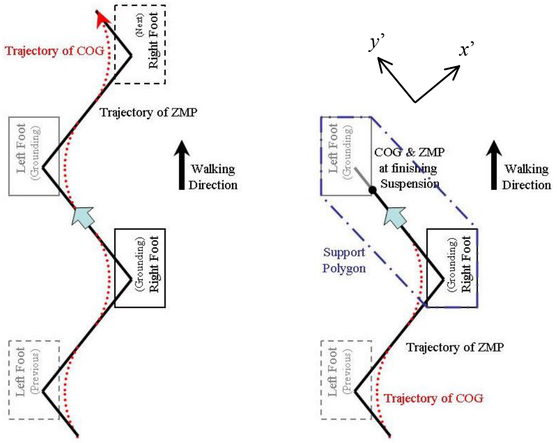
We value the original motion patterns given by “Pattern Generator.” We keep using them until we can simply change them into the suspension motions modified from them.

Now, let us consider the time when we can simply change the original pattern into the suspension motions. Our "Pattern Generator" is constructed using 3D linear inverted pendulum model. Under proper condition, a walking dynamics can be approximated by

$$p_{zmp_x} = x - (z_c / g) (d^2x / dt^2) , \qquad (5\text{-}1)$$
$$p_{zmp_y} = y - (z_c / g) (d^2y / dt^2) , \qquad (5\text{-}2)$$

where the x-axis is specified as the ordinal walking direction, (x , y) represents the horizontal displacement of the whole robot's center of mass (CoM), z_c is the height of the CoM, g is gravity acceleration, and (p_{zmp_x} , p_{zmp_y}) is the ZMP.

Figure 6 (a) shows footprints, a trajectory of ZMP reference (solid line), and a trajectory of CoM (dotted line) for forward walking. Figure 6 (b) shows footprints, the trajectory of ZMP reference, the trajectory of CoM, and a support polygon at motion suspended by our proposed system.



(a) General walks (b) Motion suspension

Figure 6. Trajectory of ZMP and that of COG

Now, we introduce a new coordinate system with x'-axis, y'-axis, and z'-axis [22]. Take the z'-axis in the direction of the vertical. Let the y'-axis be in the direction of connecting the soles of both of the supporting legs. Take the x'-axis in the perpendicular direction of y'-axis and z'-axis, as shown in Figure 6 (b).

With reference to Figure 6 (b), at the double support phase, the rigidity in the direction denoted by y'-axis is high since a closed link structure including both legs is provided, and therefore humanoid does not easily fall in the direction denoted by x'-axis. In comparison, the rigidity in the direction denoted by x'-axis is lower than that of y'-axis since a closed link structure including both legs is not provided. To put it another way, a sphere of the y'-axis support polygon is wider, and therefore humanoid is stable with respect to generated gait patterns. Figure 6 (b) also tells us that the body speed of the x'-axis locally reaches a minimum or zero around the just middle of double support phase. Furthermore, as far as current humanoid whose motion isn't fast compared with human is concerned, the direction of trajectory of CoM is almost equal to that of ZMP around the just middle of double support phase. Namely it can be considered that the body speed of the x'-axis is almost zero as far as current humanoid whose motion isn't fast compared with human is concerned. From this point of view, this paper then also employs the third idea to generate suspension motions simply.

Basic Idea III :

The acceptable period for starting suspension is around the just middle of double support phase.

This idea is illustrated as the signal of acceptable period of starting suspension, *Aflag*, in the fourth upper block of Figure 5. The status of this signal, *Aflag*, is high or low, and is decided according to a relation of both legs as follows.

$${}^{b}\boldsymbol{p}_{Rf}{}^{ref} = ({}^{b}p_{Rf_x}{}^{ref}, {}^{b}p_{Rf_y}{}^{ref}, {}^{b}p_{Rf_z}{}^{ref})^{\mathrm{T}} \equiv \boldsymbol{p}_{Rf}{}^{ref} - \boldsymbol{p}_{b}{}^{ref} \qquad (6\text{-}1)$$
$${}^{b}\boldsymbol{p}_{Lf}{}^{ref} = ({}^{b}p_{Lf_x}{}^{ref}, {}^{b}p_{Lf_y}{}^{ref}, {}^{b}p_{Lf_z}{}^{ref})^{\mathrm{T}} \equiv \boldsymbol{p}_{Lf}{}^{ref} - \boldsymbol{p}_{b}{}^{ref} \qquad (6\text{-}2)$$

$$\varepsilon_f = | ({}^{b}p_{Rf_x}{}^{ref\ 2} + {}^{b}p_{Rf_y}{}^{ref\ 2})^{1/2} - ({}^{b}p_{Lf_x}{}^{ref\ 2} + {}^{b}p_{Lf_y}{}^{ref\,2})^{1/2} | \qquad (7)$$

$$Aflag = \begin{cases} 1 & (\text{at} \quad \varepsilon_f \le \varepsilon \quad \& \quad {}^{b}p_{Rf_z}{}^{ref} = {}^{b}p_{Lf_z}{}^{ref}) \\ 0 & (\text{others}) \end{cases} \qquad (8)$$

Here, $\boldsymbol{p}_{Rf}{}^{ref}$, $\boldsymbol{p}_{Lf}{}^{ref}$, and $\boldsymbol{p}_{b}{}^{ref}$ represent a reference position vector of right foot, that of left foot, and that of body, respectively. ε is the margin of error.

As shown in the bottom block of Figure 5, we finally decide the status of start signal of suspension, *Sflag*, from *Jflag_φ* and *Aflag* by using following equation.

$$Sflag = \begin{cases} 1 & (\text{once} \quad Jflag\_\varphi = 1 \ \& \ Aflag = 1) \\ 0 & (\text{never} \quad Jflag\_\varphi = 1 \ \& \ Aflag = 1) \end{cases} \qquad (9)$$

When the status of *Sflag* is switched from zero to one (let us define this time as t_s), the process portion of "Judge of Suspension" requests that of "Suspension Motion Generator" to start generating suspension motions.

4.3. Suspension Motion Generator

To switch from original motions to suspension motions smoothly, needless to say the process portion of "Suspension Motion Generator" should generate suspension motions that are connected with the original motions. Moreover it's better that the body speed of suspension motions is smoothly reduced.

To realize these requests, when $t = t_s$, we firstly memorize $\boldsymbol{p}_{Rf}{}^{ref}$, $\boldsymbol{p}_{Lf}{}^{ref}$, $\boldsymbol{p}_{b}{}^{ref}$, $d\boldsymbol{p}_{b}{}^{ref} / dt$ that is a reference velocity vector of body, and $\boldsymbol{\varphi}^{ref}$ that is a reference vector of body posture, as $\boldsymbol{p}_{Rf_s}{}^{ref}$, $\boldsymbol{p}_{Lf_s}{}^{ref}$, $\boldsymbol{p}_{b_s}{}^{ref}$, $d\boldsymbol{p}_{b_s}{}^{ref} / dt$, and $\boldsymbol{\varphi}_s{}^{ref}$, respectively. We next modify the original patterns based on the memorized information by using following equations.

$$d\boldsymbol{p}_{b}^{mod}/dt = \begin{cases} (t_s + T_e - t)/T_e\,(d\boldsymbol{p}_{b_s}{}^{ref}/dt) & (\text{at } t_s \le t < t_s + T_e) \\ \mathbf{0} & (\text{at } t \ge t_s + T_e) \end{cases} \tag{10}$$

$$\boldsymbol{p}_{b}^{mod} = \begin{cases} [(t-t_s) - (t-t_s)^2/2/T_e]\, d\boldsymbol{p}_{b_s}{}^{ref}/dt + \boldsymbol{p}_{b_s}{}^{ref} & (\text{at } t_s \le t < t_s + T_e) \\ T_e/2\,(d\boldsymbol{p}_{b_s}{}^{ref}/dt) + \boldsymbol{p}_{b_s}{}^{ref} & (\text{at } t \ge t_s + T_e) \end{cases} \tag{11}$$

$$\boldsymbol{q}_{Rleg}^{mod} = \mathrm{IK}[\,\boldsymbol{p}_{Rf_s}{}^{ref}, \boldsymbol{p}_{b}^{mod}, \boldsymbol{\varphi}_s{}^{ref}\,] \tag{12-1}$$
$$\boldsymbol{q}_{Lleg}^{mod} = \mathrm{IK}[\,\boldsymbol{p}_{Lf_s}{}^{ref}, \boldsymbol{p}_{b}^{mod}, \boldsymbol{\varphi}_s{}^{ref}\,] \tag{12-2}$$

Here, T_e is the time period utilized for motion suspension. $\boldsymbol{p}_b^{mod}$ represents a position vector of body modified by our "Suspension Motion Generator." $\boldsymbol{q}_{Rleg}^{mod}$ and $\boldsymbol{q}_{Lleg}^{mod}$ calculated by Equation (12) are a modified joint angle vector of right leg and that of left leg respectively, and they are sent to "Stabilizer." Here, IK[$\boldsymbol{p}_{Rf_s}{}^{ref}$, $\boldsymbol{p}_b^{mod}$, $\boldsymbol{\varphi}_s{}^{ref}$] is a function of inverse kinematics to obtain six joint angles from right leg configuration, while IK[$\boldsymbol{p}_{Lf_s}{}^{ref}$, $\boldsymbol{p}_b^{mod}$, $\boldsymbol{\varphi}_s{}^{ref}$] for left leg. As shown in Equation (12), we don't consider the torso and upper limbs motion to create smooth suspension motion. The time interval for calculating Equations (10) to (12) is the same as that for original patterns generated by "Pattern Generator."

The condition to guarantee our proposed system is that the ZMP reference should be inside of support polygon in process of suspension on condition of Equations (10) to (12). As far as current humanoid is concerned, since the body speed of x'-axis at $t = t_s$ is almost zero, the condition of x'-axis is satisfied. The condition to guarantee our proposed system is then given by

$$z_c \quad |\,(dp_{by'_s}{}^{ref}/dt)/T_e\,|/g + T_e/2\,|\,dp_{by'_s}{}^{ref}/dt\,)| \le \{\,({}^{b}p_{Rf_x}{}^{ref} - {}^{b}p_{Lf_x}{}^{ref})^2 + ({}^{b}p_{Rf_y}{}^{ref} - {}^{b}p_{Lf_y}{}^{ref})^2\,\}^{1/2}/2 + \alpha. \tag{13}$$

Here, $dp_{by'_s}{}^{ref}/dt$ is the body speed reference of y'-axis at $t = t_s$ and α is almost half of foot size.

Equation (13) indicates us that our proposed method is guaranteed for current humanoid whose motion isn't fast compared with human. From our experiences using HRP-2, our proposed system has a good effect on condition that the walking speed of life-sized humanoid is less than 2.5 [km/h]. Although we observe that the rear foot is little bit forced to come up like a jackknife stop at 2.8 [km/h] walks, our proposed system successfully forces humanoids to stop immediately by one step without falling as shown in latter. Incidentally, HRP-2's 2.8 [km/h] walks come into the category of faster motions of current humanoid. From this point of view, our proposed system is practically very effective for current humanoid.

5. Experiments

To verify the validity of the proposed motion suspension system, we carried out experiments using a humanoid robot HRP-2 [10].

First, we tested whether the proposed system can predict the emergency caused by unexpected floor condition and can make a stable motion suspension. Figure 7 shows the experimental results of HRP-2's 1.35 [km/h] walks on a flat floor, while Figure 8 shows the experimental results of treading an unexpected object (height of 1 [cm]) during HRP-2's 1.35 [km/h] walks. Looking at Figure 8, it is observed that HRP-2 was stably suspended when HRP-2 treaded the unexpected object. In the case of Figure 8, the proposed system judges the emergency from the posture error. From these experiments, we confirmed the validity of our proposed system.

We also tested whether the proposed system can predict the emergency caused by landing impact force at high speed walking and can make a stop without falling. Figure 9 shows the experimental results of successful HRP-2's 2.8 [km/h] walks, while Figures 10 and 11 show the experimental results of jackknife stop during HRP-2's 2.8 [km/h] walks. In the case of Figures 10 and 11, the proposed system judges the emergency from detecting excessive impact force that sometimes occurs at high speed walking and has a possibility of making robot tip over. From these experiments, we confirmed that our proposed system practically has a good effect on averting the risk of tipping over and can make a suspension within one step without falling.

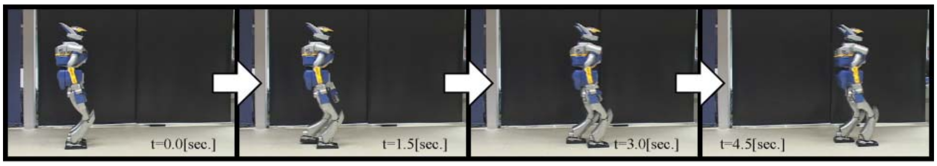


Figure 7. 1.35 [km/h] Walk (Sequence photographs: 1.5 [sec/frame])

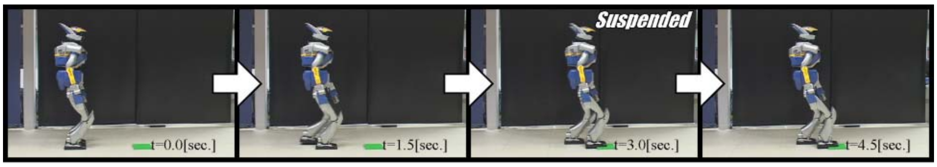


Figure 8. Motion Suspension Experiments at 1.35 [km/h] Walk (Sequence photographs: 1.5 [sec/frame])

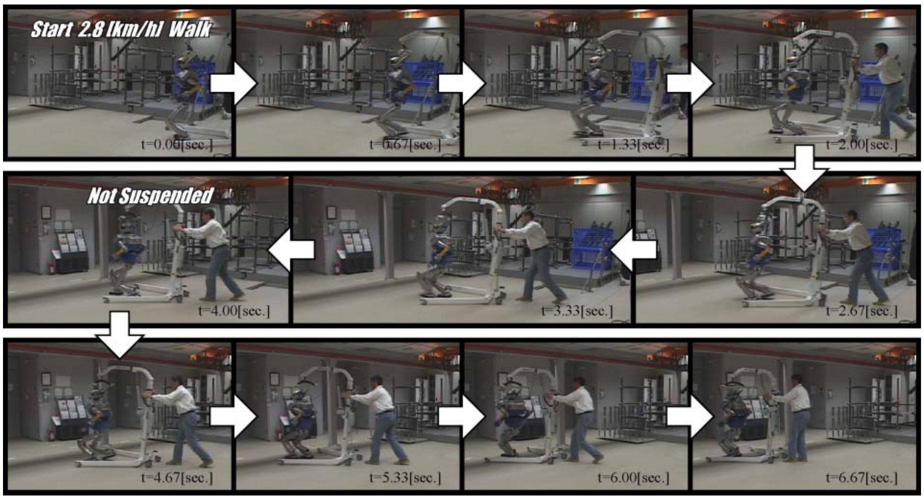


Figure 9. 2.8 [km/h] Walk (Sequence photographs: 0.67 [sec/frame])

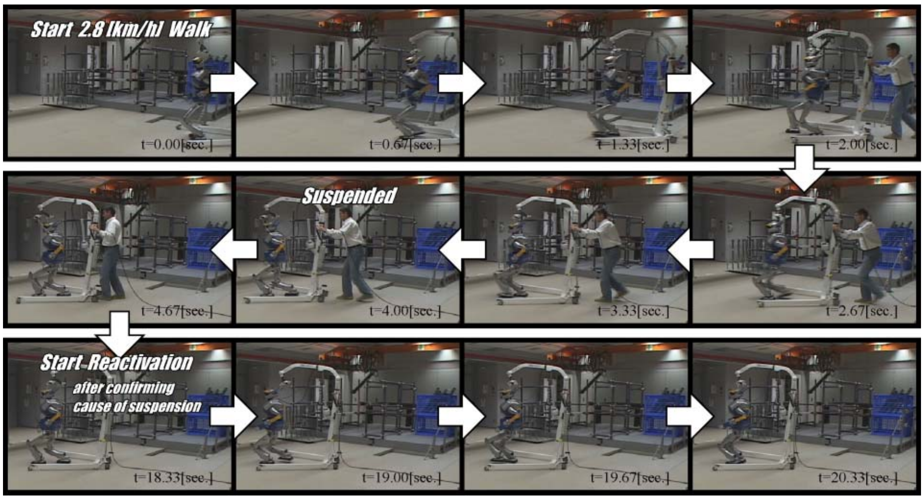


Figure 10. Motion Suspension Experiments at 2.8 [km/h] Walk
(Sequence photographs: 0.67 [sec/frame], but Interval between 8th and 9th frames: 13.67 [sec])

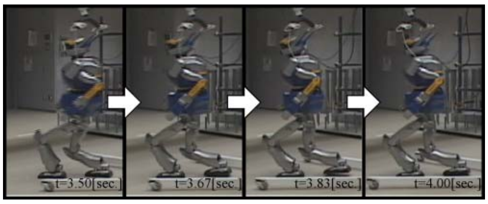


Figure 11. Jackknife Stop at 2.8 [km/h] Walk
extracted from Figure 10
(Sequence photographs: 0.17 [sec/frame])

6. Conclusions

This paper proposed the motion suspension system, which forces humanoids to stop immediately within one step in case of emergency. The proposed system consisted of a process portion of “Judge of Suspension” and that of “Suspension Motion Generator.” In that of “Judge of Suspension,” emergency prediction was decided in real-time from an accumulative judgment based on sensor information mounted on HRP-2 and pattern references and the request signal from operator. To realize that of “Suspension Motion Generator,” we employed three simple basic ideas. The first idea is that the generation of suspension motions is started at double support phase and then suspension motion is finished at double support condition. The second idea is that we keep using original pattern given from "Pattern Generator" until we can simply change them into the suspension motions modified from them. The third idea is that the acceptable period for starting suspension is around the just middle of double support phase. Our proposed method was verified from experiments using the humanoid robot HRP-2, such as experiments on treading an unexpected object and 2.8[km/h] walks experiments.

Our proposed method is simple and practically very effective for current humanoids whose motion isn't fast compared with human. However, proposed method would have no effect on condition that the walking speed of life-sized humanoid is more than 3.0 [km/h] like human. Developing a motion generator that provides stable suspension motions against original fast motions is one of our investigated future works. Improving safety by considering several emergencies in the real environment is also one of future works.

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