Robotica (2014) volume 32, pp. 325–339. © Cambridge University Press 2013
doi:10.1017/S0263574713000799

Gait motion stabilization tuning approach of biped robot based on augmented reality

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(Accepted June 25, 2013. First published online: August 2, 2013)

SUMMARY

Zero moment point (ZMP) is the most popular concept that is applied to stabilize the gait motion of a biped robot. This paper utilizes ZMP with the augmented-reality (AR) method to improve the stability of gait motion of a biped robot. The 3ds Max computer software package is used to build a virtual robot. Under an achieved joint angle data of solid robot to produce an animation of the robot's trajectory, the joint angle data are transmitted to the virtual robot to analyze the offset of the trunk. Furthermore, this investigation adopts AR to allow the user to make direct comparisons between the solid and virtual robot before and after the gait motion is corrected. The animated trajectories of the virtual robot are compared and the relevant data provide feedback to the solid robot to adjust the joint angle and further correct its posture. The experimental results reveal that the proposed scheme can improve gait motion, even when the biped robot is affected by an unexpected loading disturbance. As well as improving the stability of gait motion of a biped robot, the results of this study can also be used to teach the application of the proposed method in a robotics class.

KEYWORDS: Biped robot; Zero-moment point; Locomotion control; Augmented reality.

1. Introduction

The biped structure is one of the most versatile setups for a walking robot. A biped has almost the same movement mechanisms as a human and it is able to operate in environments that contain stairs and other obstacles.[1] Moreover, a biped robot can exhibit human-like mobility, which enables it to maneuver in areas that contain obstacles such as ladders, stairs, and rough surfaces,[2,3] Hence, the aim of developing a humanoid robot is so the robot can work cooperatively with people.[4]

The problem of controlling biped robots raises numerous considerations; for example, the intrinsic instability of two-legged motion, high-dimensional dynamics, and the existence of different phases in the walking cycle.[5] Although simple control models have the advantage of simplifying the control system design, most such models do not apply a complete walking cycle. Hence, numerous researchers have investigated the significant criterion for the stability of the walk, the trajectory of the so-called zero moment point (ZMP) beneath the robot's foot while walking.[1,2,6–15] However, a large error may exist between the actual ZMP value and the calculated value because of deviations of the physical parameters in the mathematical model and those of the real machine. Thus, the actual ZMP should be measured if it is to be used as a parameter in a method for ensuring stable walking.[1]

As mentioned above, nature has effectively solved the problem of biped locomotion during the long evolution of the human species. The analysis of basic anthropomorphic walking may be a source of interesting information that is useful in the control of a walking biped robot.[16] However, such a stability analysis needs interface devices to obtain measurements. The location of the ZMP can be obtained, computationally, using a model of the robot and measurements from joint encoders. Another method is to use direct sensory information.[2] However, employing additional sensors on the biped robot causes an extra load on the body, which results in new stability issues. Thus, how to use the virtual concept to analyze the stability of a biped robot had become a challenging issue in biped

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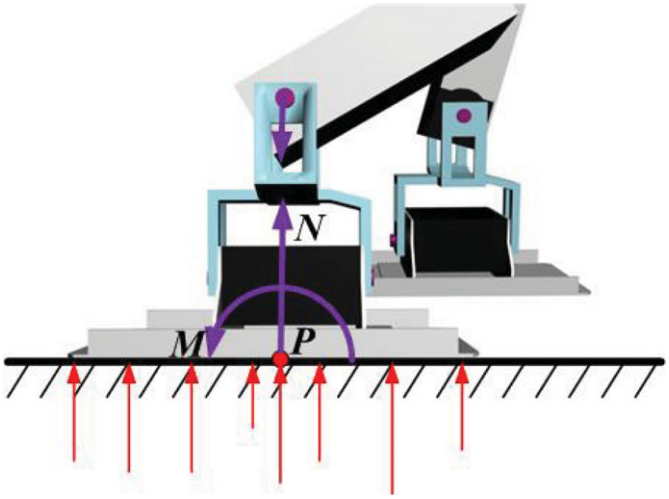


Fig. 1. (Colour online) Concept of ZMP for biped robot.

robot research. The main advantages of this concept are that the researchers do not need to install additional sensors to measure ZMP and it simplifies the hardware construction for such research.

Recently, some investigations have sought to plan a stable path and solve a similar problem of a biped robot for stabilization tuning.[17–20] One of these studies describes a method for planning walking patterns, which includes the ground conditions, dynamic stability constraints, and the relationship between walking patterns and actuator specifications.[17] Chevallereau and Aoustin[17] obtains optimal cyclic gaits for a biped robot without actuated ankles. Another elucidated ankle and hip strategies of a biped robot for the recovery of balance by a human that is subjected to a sudden external force while standing upright.[19]. Kajita *et al*. introduced a framework for biped-walking stabilization that is based on linear inverted pendulum tracking.[20] However, no research has addressed augmented-reality (AR) in the control of gait motion stability for a biped robot.

AR is the concept of overlaying computer-generated image elements over a user's field of view, "augmenting" his/her view of reality with illusionary objects.[21] The potential applications of AR for educational purposes range from simple visualization-based learning for younger students to large complex virtual laboratories where real world hardware interacts with virtual objects to create lab conditions. Recent research includes AR for robots, such as approaches to navigation,[22] manual guidance,[23] trajectory planning,[24] and locomotion control.[25–28] However, research on the AR technology that is required to control the gait motion stability of a biped robot is lacking.

This study adopts ZMP with an AR approach to improve the stability of gait motion of a biped robot. The 3ds Max computer software package is utilized to construct a virtual robot. Under an achieved joint angle data of solid robot to produce an animation of the robot's trajectory, the joint angle data are transmitted to the virtual robot to analyze the offset of the trunk. The animated trajectories of the virtual robot are compared and the data used provide feedback to the solid robot to adjust the angle of joints and further correct its posture. The experimental results indicate that the proposed approach can improve gait motion, even when the biped robot is affected by an unexpected loading disturbance. Additionally, this investigation uses AR to allow the user to make direct comparisons between the solid and virtual robot before and after the gait motion has been corrected. As well as improving the stability of gait motion of a biped robot, the results of this study can also be used to teach the application of the proposed method to a robotics class.

2. Fundamental of ZMP

The distribution of the ground beneath the robot's foot is a complicated reaction force. However, at any point, P, on the sole of the foot to the reaction can be represented by a force, N, in moment M, as shown in Fig. 1. The ZMP is simply the center of the pressure of the foot on the ground and the moment applied by the ground about this point is zero. In other words, the point, P, on the ground is

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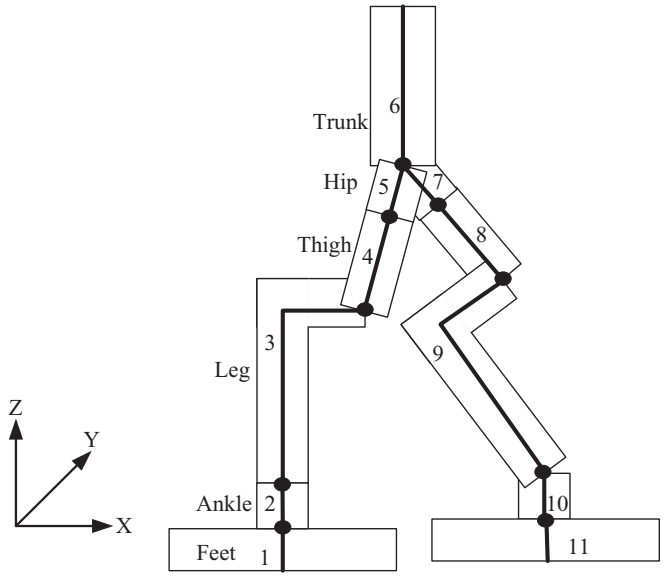


Fig. 2. Model for biped robot.

the point at which the net moment of the inertial and gravity forces has no component along the axes parallel to the ground.[1]

The mass of link is m_i with the simplifying assumption concentrated at the center of the mass of link i. The inertial rotational moment of link i is I_i; the length of link i is l_i; the distance between the center of mass of link i and its lowest point is d_i, and acceleration due to gravity is g. The angle between link i and the horizontal is θ_i (Fig. 2).

For multibody systems in the form of kinematic chains, as illustrated in Fig. 2, the ZMP can be computed using the D'Alambert's Principle, which yields the following condition[2]

$$\sum [m_i(\vec{r}_i - \vec{P}) \times (\ddot{\vec{r}}_i + \vec{g}) + I_i\vec{a} + \vec{\omega} \times I_i\vec{\omega}_i] + \sum_j (\vec{S}_j - \vec{P}) \times \vec{F}_j + \sum_k \vec{M}_k = 0, \tag{1}$$

where $\vec{r}_i$ and $\ddot{\vec{r}}_i$ are the position and acceleration of link i, respectively. In addition, $\vec{\omega}_i$ is the angular velocity and $\vec{\alpha}_i$ is angular acceleration of link i, which is the acceleration due to gravity. $\vec{F}_j$ and $\vec{M}_k$ are the external force j and moment k, respectively. Here, $\vec{S}_j$ is the position vector for $\vec{F}_j$. Thus, $\vec{P}$ is the position vector of the ZMP. The coordinates of the ZMP can be obtained by solving this equation for the X and Y components of $\vec{P}$. Some studies,[1,2] with the simplifying assumption that mass is concentrated at the center of mass of link i, the equation below is employed to obtain the coordinates of the ZMP

$$\sum_i m_i(\vec{r}_i - \vec{P}) \times (\ddot{\vec{r}}_i + \vec{g}) = 0. \tag{2}$$

Solving (2), these coordinates are obtained as

$$x_{zmp} = \frac{\sum_i m_i[(\ddot{z}_i - g)x_i - \ddot{x}_i z_i]}{\sum_i m_i(\ddot{z} - g)} \tag{3}$$

$$y_{zmp} = \frac{\sum_i m_i[(\ddot{z}_i - g)y_i - \ddot{y}_i z_i]}{\sum_i m_i(\ddot{z} - g)}. \tag{4}$$

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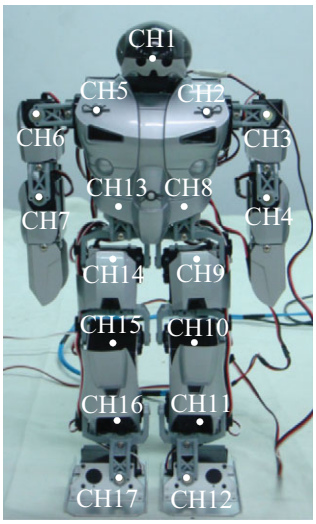


Fig. 3. (Colour online) Visualization of the biped robot system.[27]

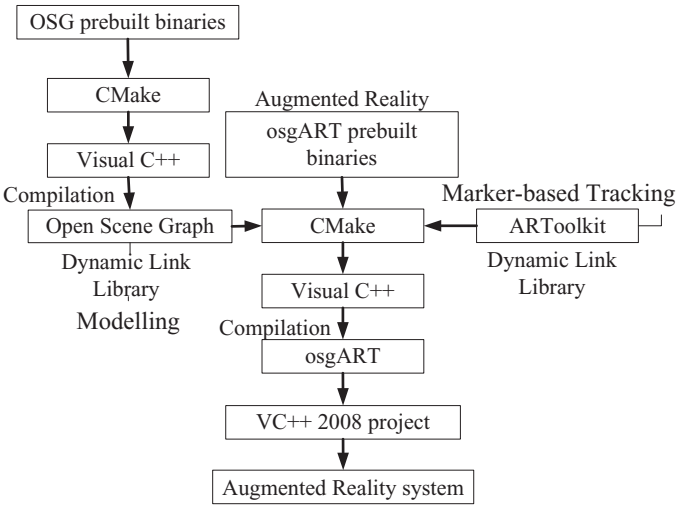


Fig. 4. Architecture for AR.

The trajectory of the ZMP poses an important criterion for the balance of biped humanoid robots. For a realistic walking pattern, ZMP trajectories must lie within the supporting polygon defined by the location and shapes of the supporting feet. Human ZMP data constitute a natural source for biped robot reference ZMP trajectories. Particularly, joint positions of humans are calculated with motion capture techniques and human ZMP trajectories are obtained by solving a ZMP equation in the form of (1) and used as reference ZMP curves to improve the genuineness of the biped robot's walking.

3. System Overview and Software Environment

Figure 3 depicts the designed structure of the humanoid robot (KHR-2HV, Konda Kagaku Co.), which has 17 joints.[29] Each joint is driven by a motor that is mounted in a linked structure. These motors are driven by a pulse-width-modulation (PWM) signal. The height, width, and the total mass are around 353 mm, 189 mm, and 1270 g, respectively. The highest walking speed with this method is around 17 mm/s.

The development of the AR engine has been performed using the standard OpenSceneGraph (OSG) with ARToolkit, which is called osgART (Fig. 4). The OSG is an open source high performance 3D graphics toolkit that is used by application developers in fields such as visual simulation, games,

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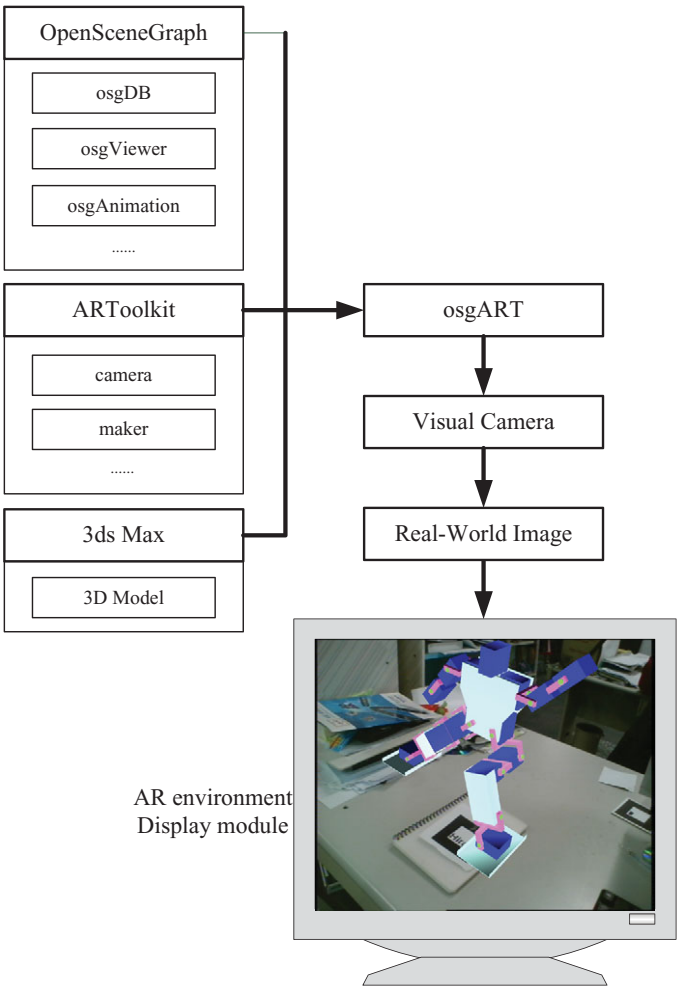


Fig. 5. (Colour online) Process of for AR environment.

virtual reality, and scientific visualization and modeling. The process of acquiring virtual image via the display module is demonstrated in Fig. 5. Thus, the main objective of the AR engine consists of merging real-world images and computer-generated graphics, which are visualized by the user via the display module. Finally, the data module loads the configuration of the design plan of the building from a DXF file. This neutral format is used by a wide variety of GIS and CAD systems (e.g., 3ds Max) as an exchange standard mechanism to store graphical information following a layer approach.[27]

4. Implementation of the Methodology

Figure 6 presents the implementation of the proposed approach. In this work, a virtual biped robot was constructed in a 3ds Max software environment (Fig. 7). Moreover, a real-world image and the virtual image via the display module are indicated in Fig. 8, respectively. The proposed process for gait motion tuning of the biped robot has three major aspects: creating virtual biped robot model, generating learning behavior in AR environment, and sending the learning results to solid robot (real-life environment).

Hence, the specifications of the components and actuators in the solid robot must be verified firstly. The virtual robot has the following regions: biped feet, hand, head, and trunk. A 3D virtual robot model drawing based on a size ratio of 1:1 with the real robot is constructed in 3ds Max software with the same operating characteristics as the solid robot. Therefore, the parameters associated with the virtual robot are almost the same as those associated with the solid robot.

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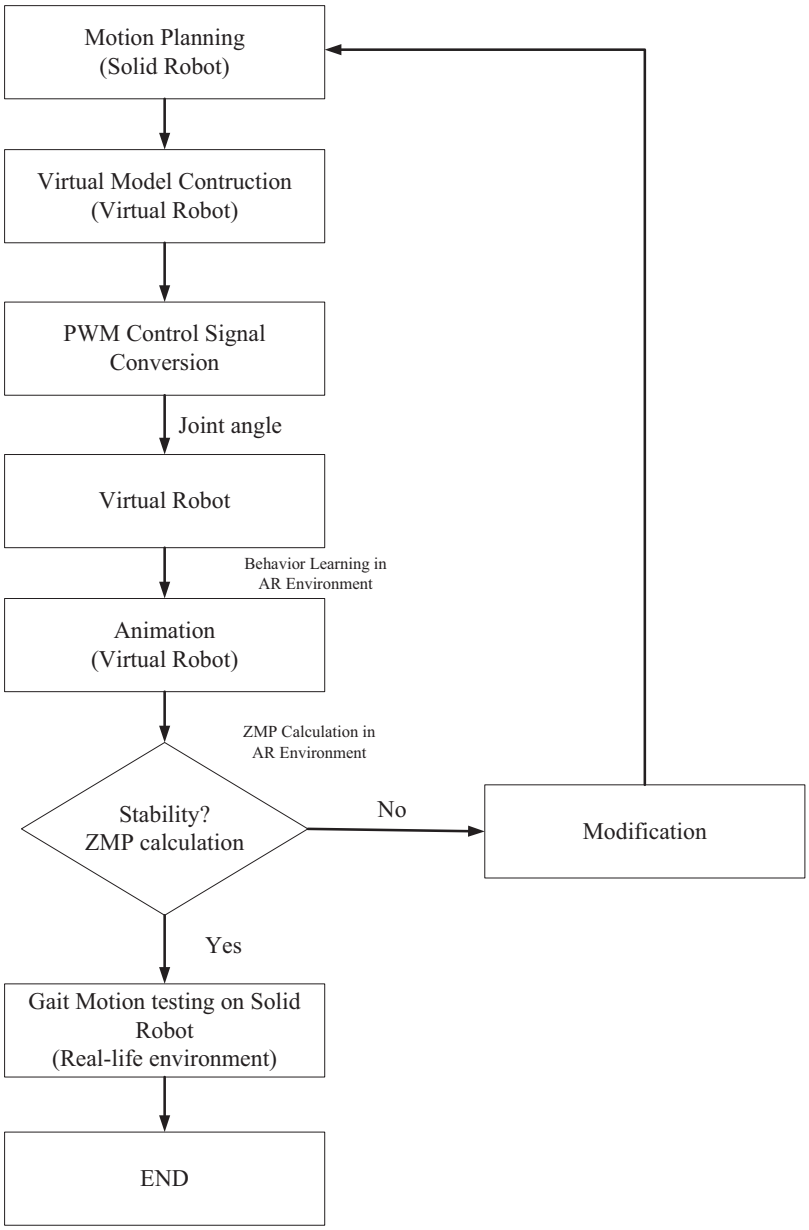
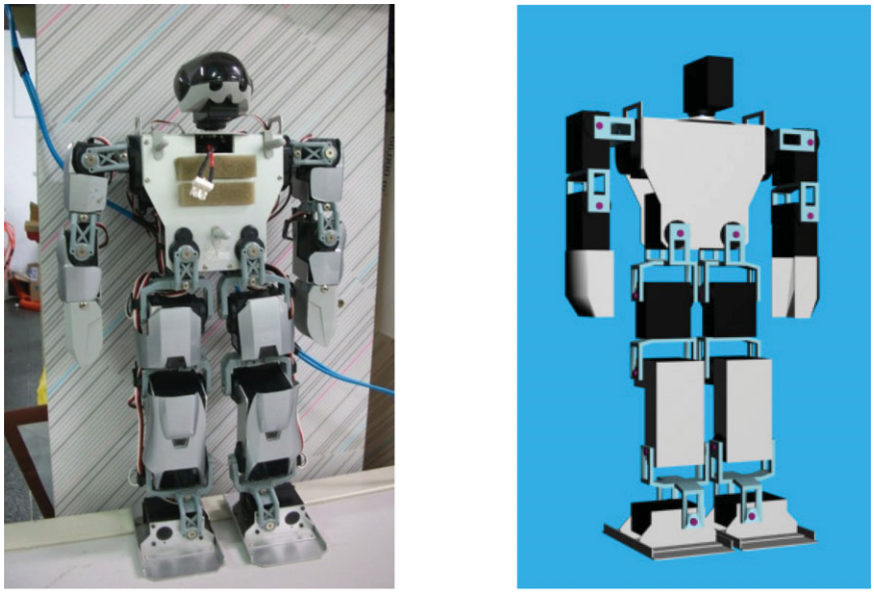


Fig. 6. Implementation of the proposed approach, (a) solid robot (b) virtual robot.

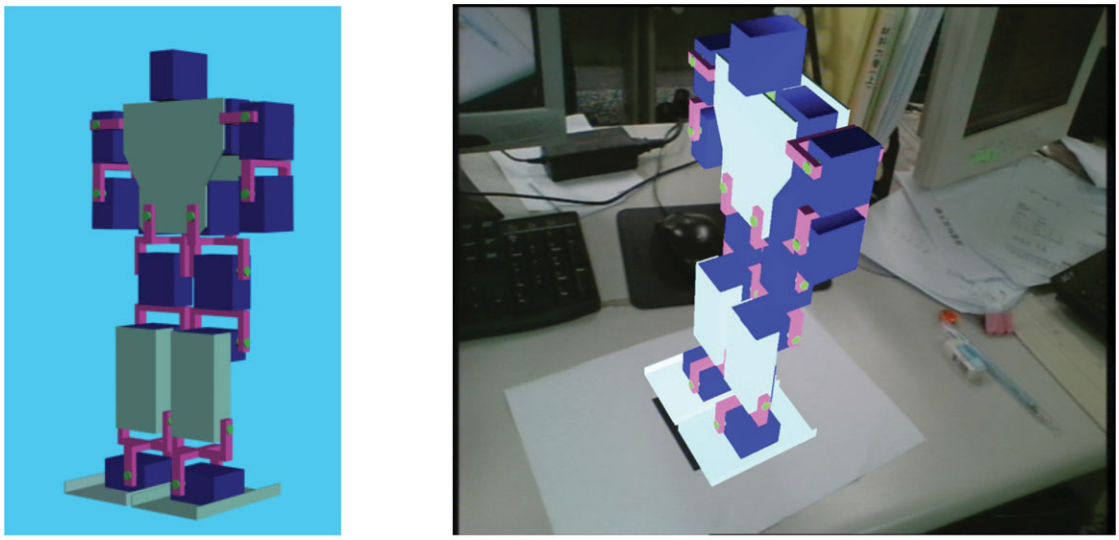
Because the motors of the solid robot are driven by pulse-width-modulation (PWM) signal type, it needed to converse the signal from PWM to the joint angle. After mapping this path to the joint space, a time-scale trajectory was obtained, subjected to robot kinematics and dynamics constraints. Hence, the trajectory of the biped motion was fed to simulate the virtual robot performing the trajectory in the real-life environment for the user to evaluate, visually, the stability of the biped motion. Since there is no actions torques that cause robot to fall down at the ZMP, the ZMP is very important for walking robot and generally used as dynamic criterion for gait motion and control.[11] In the walking of the biped robot, the ZMP is positioned inside of the footprint of the supported foot or within the supported polygon. Thus, the ZMP calculation can be solved in the AR environment and used to judge the stability of gait motion in this study. Finally, the biped motion can be transferred into the controller codes, which can be executed on a solid robot to verify gait motion performance. The main advantages of this concept are that the researchers do not need to install additional sensors to measure ZMP and it simplifies the hardware construction.

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(a) Solid Robot (b) Virtual Robot

Fig. 7. (Colour online) Solid and virtual robots construction.



(a) Real-World image (b) AR environment

Fig. 8. (Colour online) Virtual robot and AR environment, (a) real-world image (b) AR environment.

5. Experiments and Discussion

5.1. Biped robot walking on horizontal planar surface

This section presents the experimental results concerning the proposed methodology for tuning the standing posture of a biped robot system. To confirm the performance of the proposed methodology, the researchers examined the biped robot walking on a horizontal planar surface using the proposed stabilization tuning approach in real-time experiments. Through the various simulation capabilities provided in the proposed AR environment, the users previewed the simulated motion, perceived any possible overshoot, and resolved discrepancies between the planned and simulated paths prior to the execution of a task.

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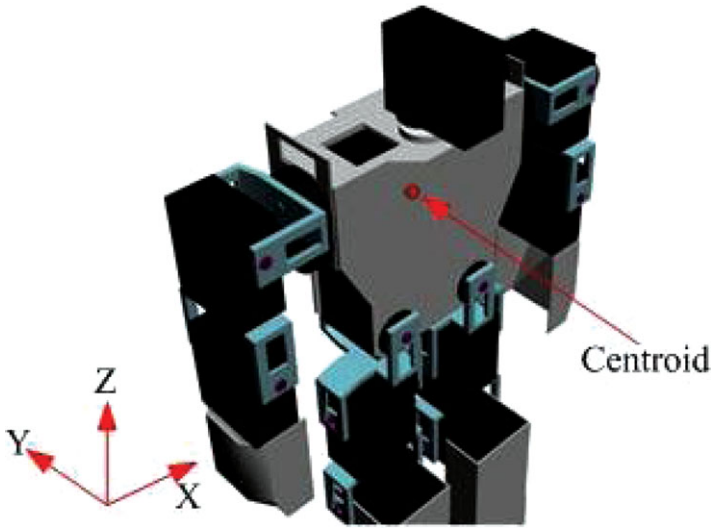


Fig. 9. (Colour online) Coordinates for the robot.

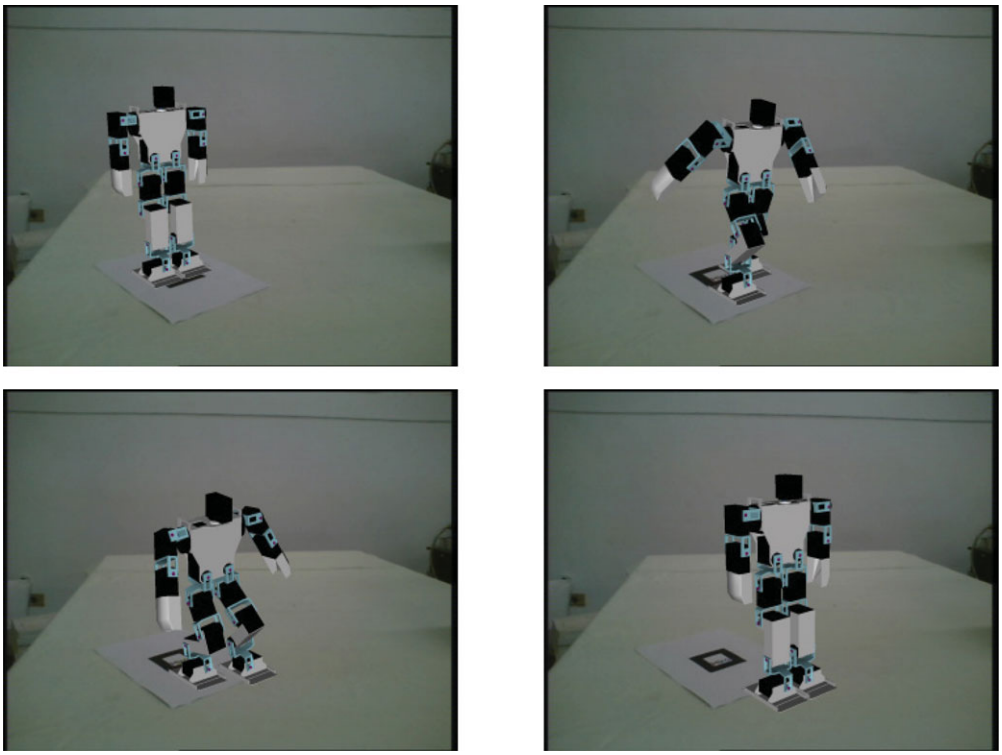


Fig. 10. (Colour online) AR animation for Model 1.

A case study of the use of the proposed methodology to assist a user to improve the stability of gait motion of a biped robot is presented. Based on the gait motion of the solid robot, two virtual robots (Model 1 and Model 2) were constructed to analyze the stability of the biped gait motion. The main goal of this work is to improve this stability. Primary gait motion planning is based on the operator's knowledge. The operator decomposes the gait motion into 22 steps to generate a series small biped motion as the basis of a pretuning model (Model 1). Model 1 is the animated model. It is directly controlled according to the operator's knowledge[29]; this process is called pretuning. The operator's knowledge is based on the walking gait characteristics of a human. Observations of human behavior are useful in modeling the motions of a biped robot. The gait stabilization tuning algorithm elucidates walking characteristics by measuring human motion during locomotion. However, the only required

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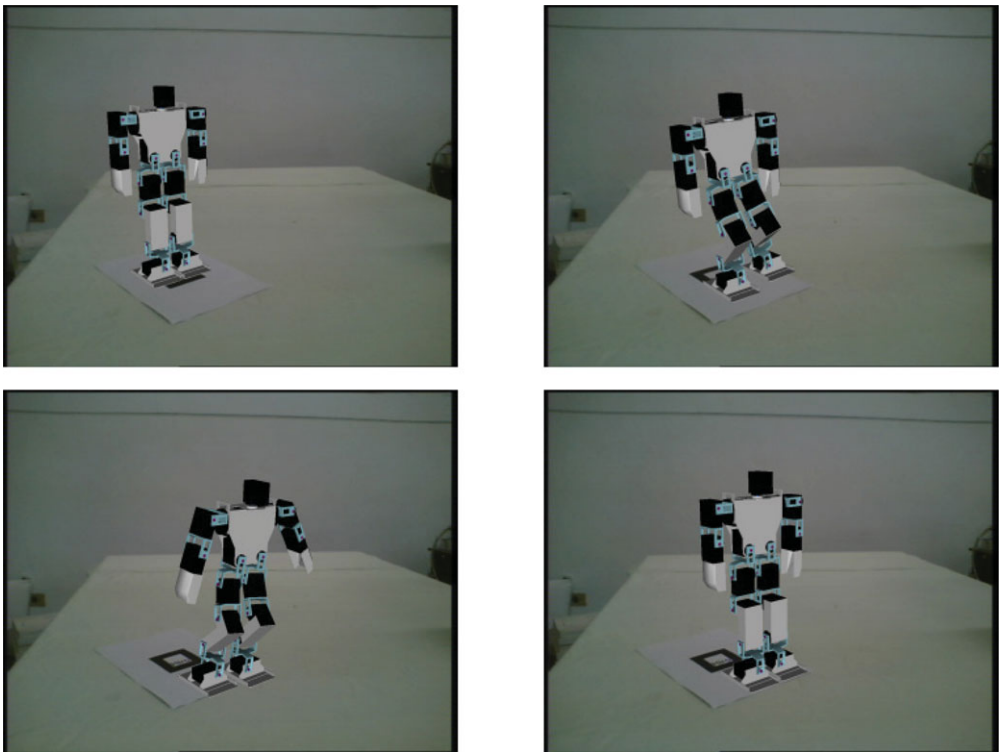


Fig. 11. (Colour online) AR animation for Model 2.

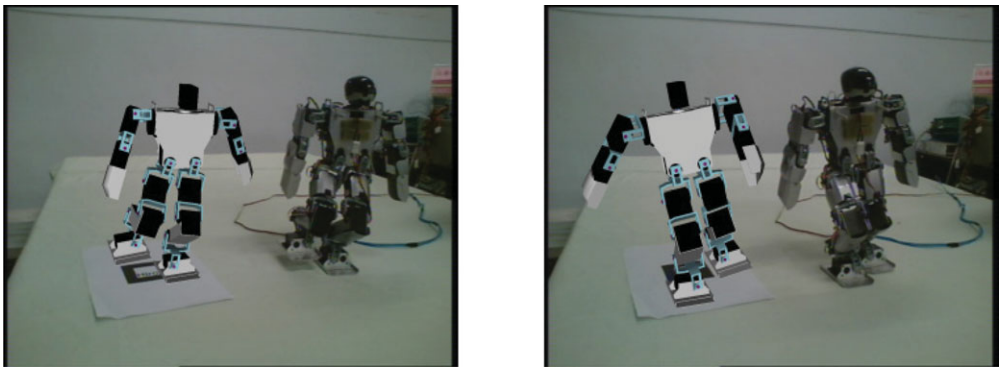


Fig. 12. (Colour online) Solid robot gait motion design by using Model 1 (pretuning).

knowledge of the operator is to provide a rough estimate of for controlling the motor torque at each joint. The method depends only on the knowledge of the operator and does require ZMP calculation. Thus, ZMP data are required to improve the walking gait. Consequently, the posttuning model (Model 2) was the animated model that incorporated the ZMP concept. Model 2 introduces the ZMP concept to Model 1 to adjust the stability of gait motion. The ZMP can be calculated in the AR environment and used to judge the stability of gait motion. The walking pattern of a stably walking biped robot should satisfy the condition that the ZMP of the robot is always in the region of stability. Therefore, the ZMP point of the virtual robot in the AR environment should be checked and modified at each step of the gait pattern.

The modification of joint angles is the main basis of the proposed tuning approach. The selection of joint angles of biped robot is based on solutions for the inverse kinematics (adopted from Ref. 11). Under an achieved joint angle data of solid robot to produce an animation of the robot's trajectory, the joint angle data are transmitted to the virtual robot to analyze the offset of the trunk. A comparison of the animated trajectories of the virtual robot provides data that are fed back to the solid robot to adjust its joint angles and correct its posture.

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Table 1. Normalized deviation for Model 1 (pretuning) and Model 2 (posttuning).

	X-axis deviation (horizontal offset)	*Y*-axis deviation	*Z*-axis deviation (vertical offset)
Model 1 (Pretuning)	34.25 mm	182.3 mm	132.19 mm
Model 2 (Posttuning)	12.57 mm	122.7 mm	77.61 mm

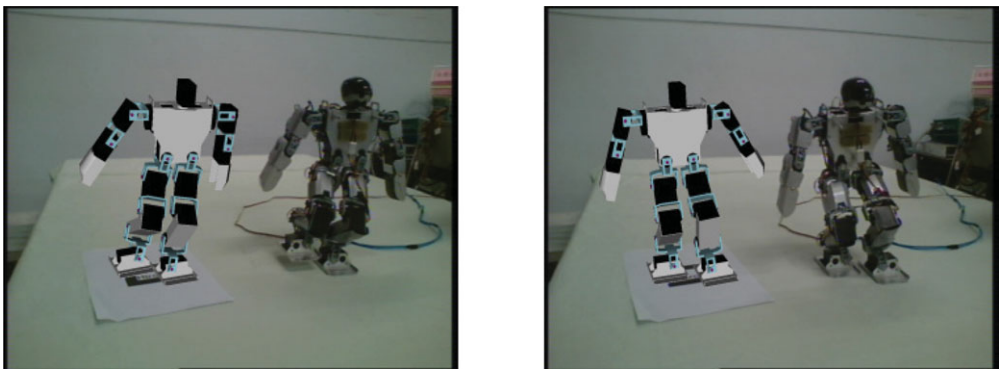


Fig. 13. (Colour online) Solid robot gait motion design by using Model 2 (posttuning).

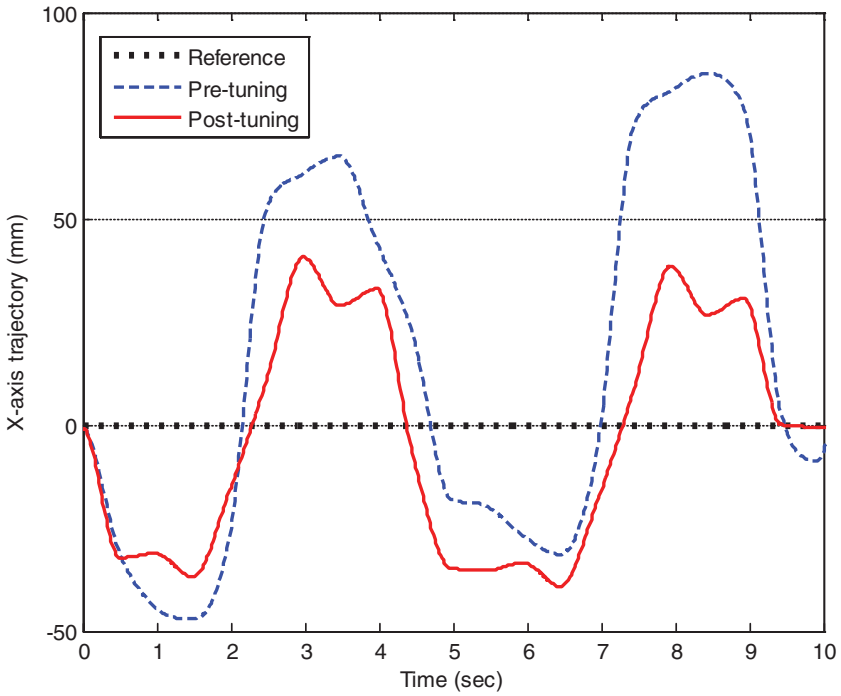


Fig. 14. (Colour online) Model 1 (pretuning) and Model 2 (posttuning) on *X*-axis trajectory.

The coordinates of the robot are demonstrated in Fig. 9. The reference point for the performance comparison was defined as the centroid point of the torso. The following biped gait motion analysis was use as a reference point for performance comparison. The *X*-axis represents the horizontal offset of the trunk and the *Y*-axis indicates the forward walking distance of the biped robot. Finally, the *Z*-axis reveals the vertical offset of the trunk while in motion. Consequently, Figs. 10 and 11 demonstrate animation in the AR environment. The solid robot gait motion design, using Model 1 (pretuning) and Model 2 (posttuning) is indicated in Figs. 12 and 13, respectively.

Figures 14–16 show the trajectory of *X*-, *Y*-, and *Z*-axis with Model 1 (pretuning) and Model 2 (posttuning) for the biped robot walking on a horizontal plane, respectively. The *X*-axis represents

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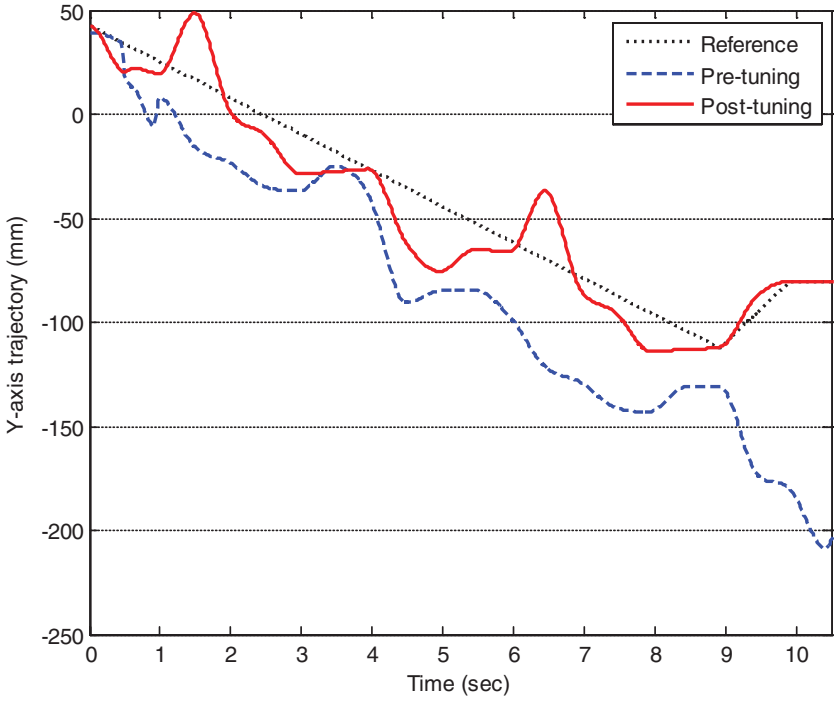


Fig. 15. (Colour online) Model 1 (pretuning) and Model 2 (posttuning) on *Y*-axis trajectory.

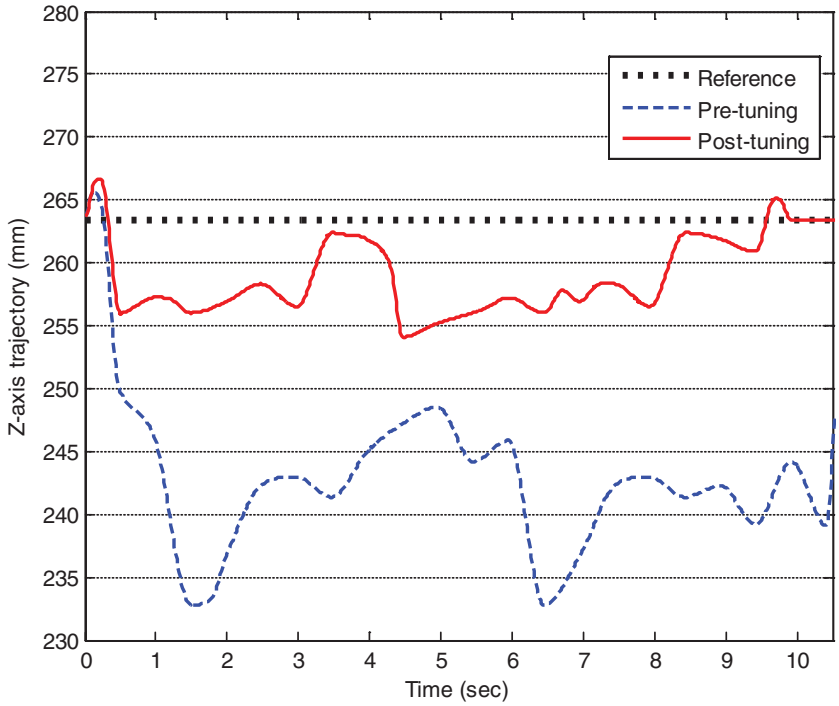


Fig. 16. (Colour online) Model 1 (pretuning) and Model 2 (posttuning) on *Z*-axis trajectory.

the horizontal offset of the trunk while in motion. It was observed that a large offset occurs with the supporting foot during the replacement of the gait (Fig. 14). This experimental finding indicates that Model 2 (posttuning) markedly improved trunk offset.

Moreover, the normalized root-mean-square (RMS) of the horizontal offset of the trunk for the biped robot decreased from 34.25 to 12.57 mm, which indicates that the proposed methodology reduced the horizontal offset of the trunk by roughly 63.3% (Table I). Similarly, the normalized RMS

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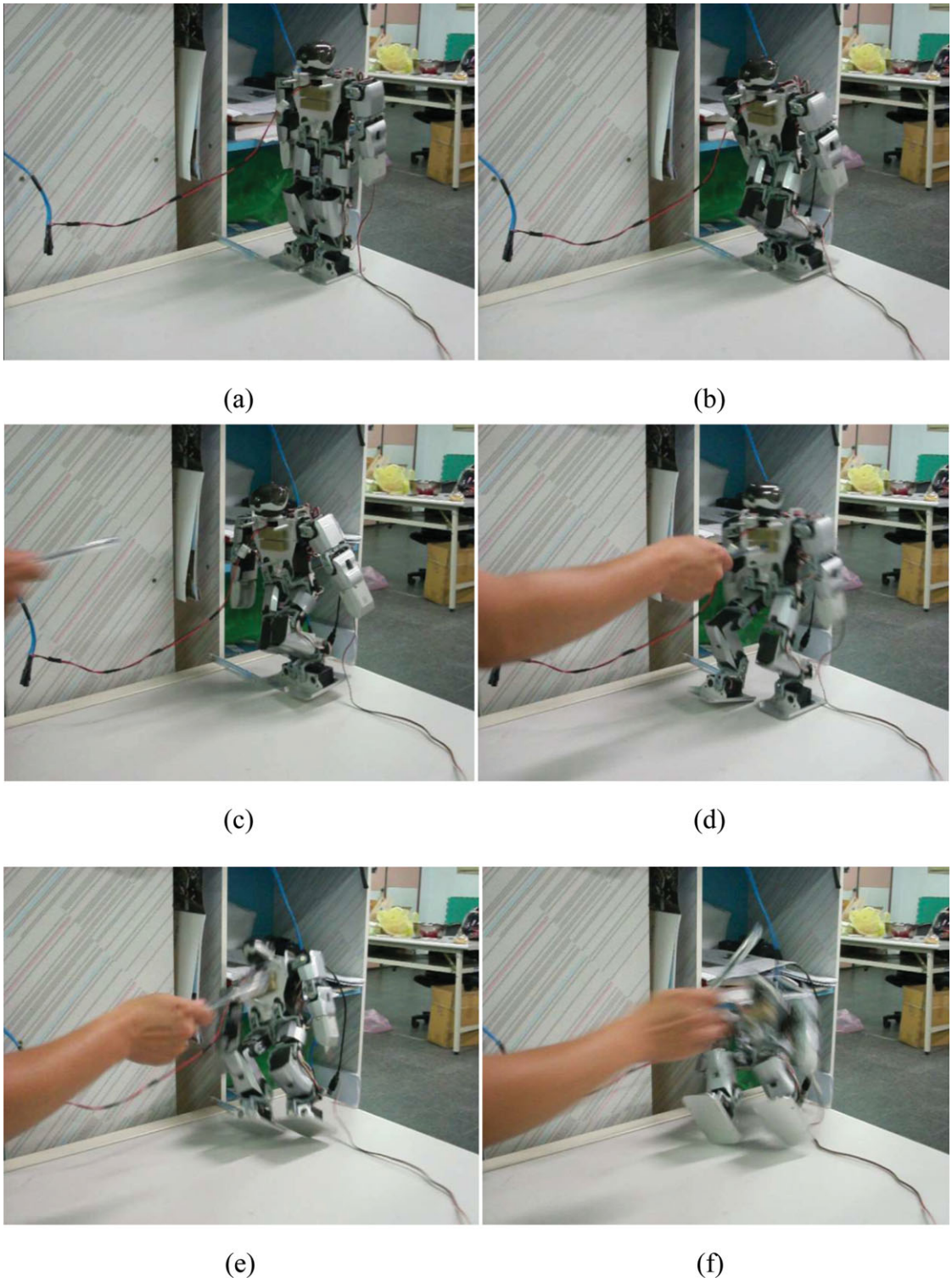


Fig. 17. (Colour online) Solid robot gait motion design by Model 1 (pretuning) subjected to sudden impact.

of the vertical offset of the trunk for the biped robot decreased from 132.19 to 77.61 mm, or by around 41.29%. The trunk offset when the gait motion was substantially reduced. The effectiveness of the biped robot stabilization posture was verified when Model 2 was applied. Moreover, the tracking error (RMS) of forward walking distance reduced from 182.3 to 122.7 mm, a 32.7% reduction. These

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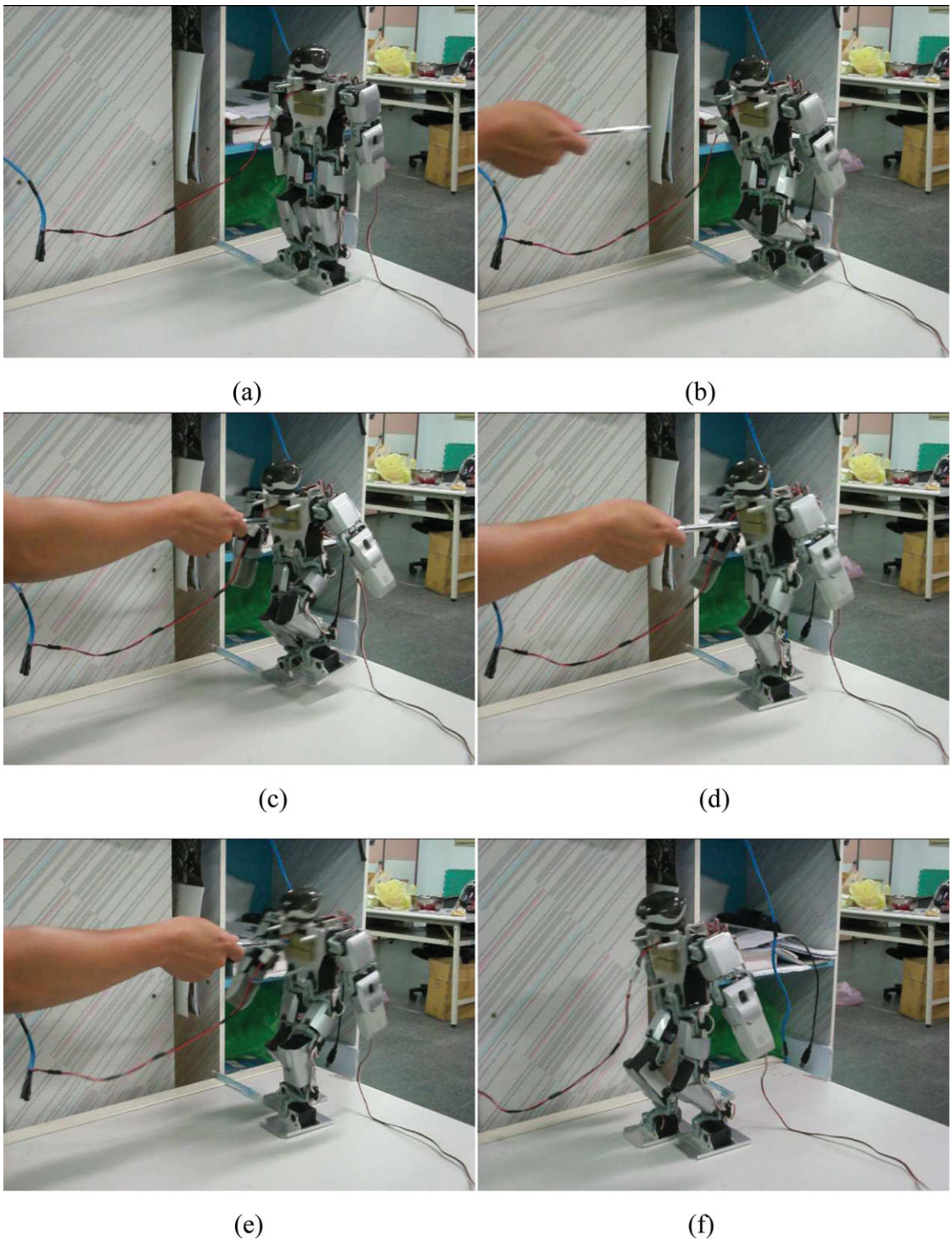


Fig. 18. (Colour online) Solid robot gait motion design by Model 2 (posttuning) subjected to sudden impact.

experimental results reveal that effective tracking performance was achieved and the offset of the trunk could be eliminated.

5.2. Biped robot walking on horizontal planar surface subject to sudden impact

The unknown object was suddenly impacted on the biped robot as a load disturbance. The solid robot gait motion design under unexpected impact, using Model 1 (pretuning) and Model 2 (posttuning) is demonstrated in Figs. 17 and 18, respectively. While imposed by an impact, the solid robot will fall

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down during a walking period (Fig. 17). The sudden impact has great effect on the gait motion for the biped robot gait trajectory designed by Model 1 (pretuning). Alternatively, experimental results (Fig. 18) demonstrate that Model 2 tuning methodology achieves good gait motion stability during a walking period. While imposed by an impact, the solid robot is still walking on the floor, not fall down during a walking period (Fig. 18). As seen, the proposed tuning methodology (Model 2) has performs much better than the tuning methodology (Model 1). The performance of the Model 2 tuning scheme is not significantly affected by changes to system parameters, demonstrating the effectives of the proposed tuning scheme (Model 2) in walking behavior, even when the biped robot is caused by unexpected loading disturbance. Experimental responses show that the proposed tuning methodology (Model 2) is robust to the parameter variation. Thus, this research adopted ZMP with AR methodology for ensuring stable walking for the biped robot. Consequently, an AR-based system was proposed to assist users in programming the humanoid robot and improve the stability of its gait motion.

6. Conclusions

In this paper, an AR-based system was proposed to assist users in programming the humanoid robot and improve the stability of its gait motion. A virtual robot model, which replicated a solid robot, was used to perform and simulate the task planning process. The interactive simulation allows users to preview, evaluate optimization outputs, and select a practical trajectory profile while considering path duration and actuator. Meanwhile, users can observe the link that is most likely to deviate from the path and visualize the instantaneous actuator usage when the virtual robot performs the planned trajectory. To confirm the performance of the controller, the biped robot, walking on a horizontal planar surface using the proposed stabilization tuning approach, was examined in real-time experiments. These experimental results revealed that effective tracking performance was achieved and the offset of the trunk could be eliminated. The benefit of this stabilization method is not only to reduce the duration of transient oscillations, but also to suppress instability. The main contribution of the approach firstly proposes the incorporation of AR and ZMP concept in robot programming to improve the stability of gait motion for the biped robot in the related research. Furthermore, this approach assists the uses in evaluating trajectory and provides cues and options to tune controller parameters. As well as improving the stability of gait motion of a biped robot, the results of this investigation can also be used to teach the application of the proposed method to a robotics class.

Acknowledgements

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under contract no. NSC 96-2221-E-231-01-MY3. Ted Knoy is appreciated for his editorial assistance.

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