Study on the Real-Time Walking Control of a Humanoid Robot Using Fuzzy Algorithm

Jung-Shik Kong, Eung-Hyuk Lee, Bo-Hee Lee, and Jin-Geol Kim

Abstract: This paper deals with the real-time stable walking for a humanoid robot, ISHURO-II, on uneven terrain. A humanoid robot necessitates achieving posture stabilization since it has basic problems such as structural instability. In this paper, a stabilization algorithm is proposed using the ground reaction forces, which are measured using FSR (Force Sensing Resistor) sensors during walking, and the ground conditions are estimated from these data. From this information the robot selects the proper motion pattern and overcomes ground irregularities effectively. In order to generate the proper reaction under the various ground situations, a fuzzy algorithm is applied in finding the proper angle of the joint. The performance of the proposed algorithm is verified by simulation and walking experiments on a 24-DOFs humanoid robot, ISHURO-II.

Keywords: Force sensing resistor, fuzzy algorithm, humanoid robot, stabilization.

1. INTRODUCTION

Instability is one of the major defects in humanoid robots. Recently, various methods on the stability and reliability of humanoid robots have been actively studied. Several researches in this area have applied the ZMP (Zero Moment Point) as the index for the stability of a humanoid robot. The ZMP was first proposed by Vukobratovic, and the ZMP stability criteria states that the robot will not fall down as long as the ZMP remains inside the convex hull of the foot-support [1].

Previous researchers have proposed either a controller or compensator from the difference between the real ZMP and desired ZMP that was generated off-line [2]. The method of real-time stabilization involves maintaining the ZMP within a table margin by operation of the upper body or waist joint [3]. A COG Jacobian can also be employed as an index for stability [4]. Furthermore, some methods have been proposed for control of the stabilities such as the adaptive neuro-fuzzy system [5,13], Genetic Algorithm [6], optimal preview control [7], and incremental fuzzy control [8]. Besides the above methods, control of acceleration through variation of the time interval of trajectory [9], a method using a feedback algorithm [10], a method of integrating pre-generated basic motion [11], and control of the upper body orientation and foot torques have been proposed. However, the aforementioned researches generally require a heavy operating load, simplification of the model, or a regard for external forces as the main factor of instability. Recently, some studies of stabilization have been reported by analyzing ZMP, landing phase, and body posture under uneven terrain [12]. In this paper, a real-time walking stabilization method utilizing a fuzzy algorithm under uneven terrain is proposed. We focused most of our interest on landing phase. The ground reaction forces, measured by FSR sensors on the sole, are used to assess the ground condition and the robot posture. The organization of this paper is as follows. In Section 2, the walking strategy and the stabilization algorithm are presented. Simulation and experiment results for the proposed method are given in Section 3, followed by conclusions in the final section

Manuscript received June 11, 2007; revised January 2, 2008; accepted March 21, 2008. Recommended by Editorial Board member Dong Hwan Kim under the direction of Editor Jae-Bok Song.

Jung-Shik Kong is with the Department of Micro robot, Daeduck College, 48, Jang-dong, Yuseong-gu, Daejeon 305-715, Korea (e-mail: jskong@ddc.ac.kr).

Eung-Hyuk Lee is with the Department of Electronic Engineering, Korea Polytechnic Univ., 2121, Jungwang-dong, Siheung city, Kyunggido 429-793, Korea (e-mail: ehlee@kpu.ac.kr).

Bo-Hee Lee is with the Department of Electrical Engineering, Semyung Univ., 579, Sinwal-dong, Jaechon city, Chungbuk 390-711, Korea (e-mail: bhlee@semyung.ac.kr).

Jin-Geol Kim is with the School of Electronic and Electrical Engineering, Inha Univ., Yonghyun-dong, Nam-gu, Incheon 402-751, Korea (e-mail: john@inha.ac.kr).

2. WALKING PATTERN AND STABILIZATION ALGORITHM

2.1. Walking pattern

Basically, a robot walks with the trajectory generated previously assuming even terrain. If

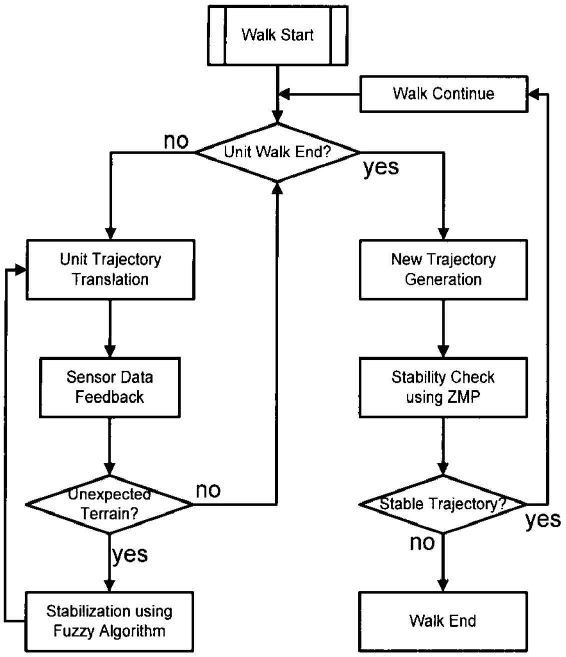


Fig. 1. Walking algorithm.

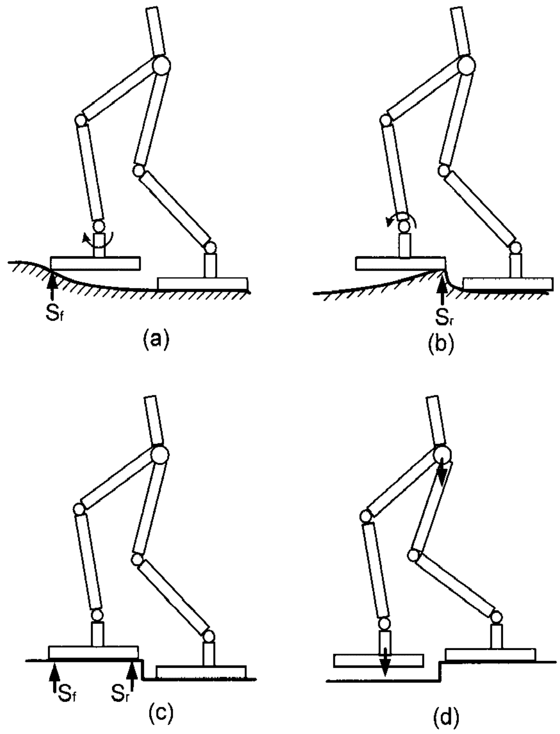


Fig. 2. Irregular ground condition.

different values from the expected sensor are measured during walking, the robot should be deployed using the stabilization algorithm. Fig. 1 presents the walking algorithm.

When the robot is walking, it measures the ground reaction forces in real-time and utilizes them as inputs to the controller. When the control of the robot is interrupted by an unexpected situation or a unit step has ended, the new trajectory should be generated according to the changed situation. The newly generated trajectory passes through stability verification based on the ZMP criterion. Once the stability of the trajectory is guaranteed, the robot becomes able to resume the walking.

2.2. Stabilization algorithm (I)

In order to ensure that the robot walks stably, the motion should basically be stable and smooth. In addition, the robot must be able to detect approaching situations, and to control itself accordingly. When this control concept is applied, the robot is able to walk stably coping with unexpected external disturbances.

A robot can face unexpected situations during walking such as projecting ground, depressed ground, and projected ground as described in Fig. 2.

To guarantee total stability for various environments, the first step of the stabilization process considered here is to decide a pattern of action. A robot is willing to walk at the trajectory generated previously, assuming even terrain. The feet of the robot are parallel to the ground in each step of planned walking. In addition, the robot knows the landing position of the swing leg. The robot monitors the ground reaction forces and walking time from the commencement of walking. During walking, if reaction forces are detected through the front or rear sensor at an unexpected moment, a situation such as that depicted in Fig. 2(a) or (b) is forecasted. In this case, the robot can maintain balance through proper rotation of the ankle pitch. When the whole foot reaches the ground earlier than the predicted moment, projected ground, as in (c), is forecasted. In this case, the robot can choose to ignore the planned trajectory from this point in time and generate a new trajectory before walking is resumed. Conversely, when there is measured data at an expected moment, the robot forecasts depressed ground, as in (d). In this case, the robot comes down with the swing foot to the settled depth. If the foot does not make contact by the end of planed walking, the robot returns to the starting posture and then waits for the operator's command or looks for another path. So, the robot is able to divide the walking pattern according to the situation. The robot maintains stability and continues walking through the chosen proper pattern under various ground conditions.

2.3. Stabilization algorithm (II)

The unstable situation considered for control in this paper is projecting ground, as indicated in Fig. 2(a) and (b). In the case of Fig. 2(c) and (d), because additional operation is not needed for the trajectory, the countermeasure is relatively simple, such as stopping and returning. However, in the case of Fig. 2(a) and (b), the standard of stability must be determined, and it must be decided how to operate the robot in order to satisfy this standard. Furthermore, the operation for each joint value is performed within

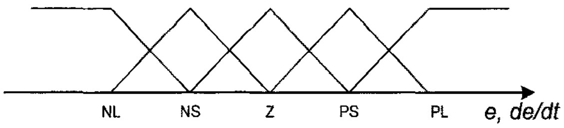


Fig. 3. Input membership function.

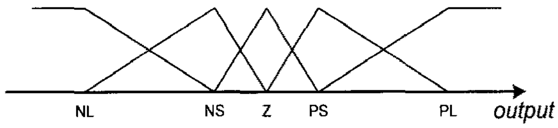


Fig. 4. Output membership function.

the fixed walking time, and the operator must check again whether the robot is stable. In accordance with the aforementioned factors, a complex algorithm is required. This paper proposes an ankle joint control method involving application of a fuzzy algorithm. The proposed method takes data from the sole sensor of the foot on the swing leg as the controller input, and variation of the ankle joint angle as controller output.

In order to perform the fuzzification, the difference value between the front sensor and rear sensor is established as the error of the controller input, and variation of the difference is set up as the differential error of the controller input. The fuzzification of the present state is performed based on these input values using the input membership function described in Fig. 3. In the process of fuzzification, five values of the center are used for the input membership function. The values of the center are established based on the range of measurement. In Fig. 3, 5 fuzzy sets have been used to represent sensor data according to the difference of the front and rear sensor of the foot. NS means a half possibility of overturn and NL is the 80 percent when the center of mass of the robot comes to the toe of the supporting foot.

We generate the rule-base model with the result of fuzzification based on robot states and ground condition like the following control rule:

$$\text{If } e \text{ is } A_1 \text{ and } \dot{e} \text{ is } A_2 \text{ then } u \text{ is } B, \quad (1)$$

where A_1 is the difference between sensor values, A_2 is the variation of the difference, and B is the variation of angle. The result of the fuzzy algorithm at the control rule, given by (1), is used to obtain the quantity of rotation added at the ankle joint. Table 1 represents the total rule-base.

NL, NS, Z, PS, and PL denote Negative Large, Negative Small, Zero, Positive Small, and Positive Large, respectively. The inference engine of the current robot condition is performed using this language rule based on the rule-base. The variation of the ankle joint angle is determined through defuzzification of this inference result. In order to decide output of this variation, the center average method is used as a defuzzification process. Fig. 4 presents the output membership function for the fuzzy algorithm.

Table 1. Rule-base of fuzzy algorithm.

		$\dot{e}$				
		NL	NS	Z	PS	PL
e	NL	NL	NL	NL	NS	NS
	NS	NL	NS	NS	NS	NS
	Z	Z	Z	Z	Z	Z
	PS	PS	PS	PS	PS	PL
	PL	PS	PS	PL	PL	PL

Because the output membership function gives much influence for the performance of the controller, in this paper, the parameters of this function are adjusted repeatedly and determined heuristically.

2.4. Resuming walking

When the stabilization algorithm is completed and then a unit step is ended, the robot generates the new trajectory for the changed robot posture and ground condition. The new trajectory is passed by the stability verification through the ZMP criterion. A stable ZMP should be inside the supporting area that circumscribes one or two soles in support. If the stability of the trajectory is guaranteed, the robot resumes walking. The ZMP can be computed as follows:

$$x_{ZMP} = \frac{\sum_{i=0}^{8} m_i(\ddot{z} + G_z)x_i - \sum_{i=0}^{8} m_i(\ddot{x} + G_x)z_i}{\sum_{i=0}^{8} m_i(\ddot{z} + G_z)}, \quad (2)$$

$$y_{ZMP} = \frac{\sum_{i=0}^{8} m_i(\ddot{z}_i + G_z)y_i - \sum_{i=0}^{8} m_i(\ddot{y}_i + G_y)z_i}{\sum_{i=0}^{8} m_i(\ddot{z}_i + G_z)}, \quad (3)$$

where x_{ZMP} presents the ZMP of the saggital direction and y_{ZMP} presents the ZMP of the lateral direction of the robot. (x_i, y_i, z_i) is the mass center of link i in the coordinate system, m_i is the mass of link i, and G_i is the gravitational acceleration. $(\ddot{x}_i, \ddot{y}_i, \ddot{z}_i)$ is the linear acceleration of the mass center of link i.

3. SIMULATION AND EXPERIMENT

3.1. Humanoid robot and sensor system

The simulation is based on a humanoid robot, ISHURO-II. The robot has a height of about 950mm,

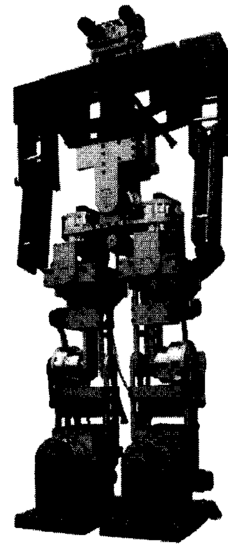


Fig. 5. Humanoid robot, ISHURO-II.

a weight of roughly 35kg, and 24 DOFs. Fig. 5 shows ISHURO-II.

The robot determines a walking pattern using the ground reaction forces measured from the sole. Fig. 6 shows the architecture of the sole system for measurement of ground reaction forces.

ISHURO-II measures these forces using FSR sensors fixed at the sole, and the obtained data is employed as the input of the stabilization algorithm. FSR sensors are generally used for measuring the dynamic force by the variation of resistance in the force or pressure acting on the surface. FSR sensors are economical, thin, light, and easy to use. In addition, Moving-Average Filter is applied to reduced influence of the disturbance by sensor noise. Equation (4) shows the Moving-Average Filter.

$$R(n) = \frac{\sum_{i=0}^{k} f(n-i)}{k} \tag{4}$$

In (4), $f(n)$, k, and $R(n)$ are the raw sensor data at n time, orders of filter, and filtered data, respectively.

Four sensors are equipped at 4 corners of each foot. In order to minimize impact and deformation, and also to distribute repulsive power, the sole is composed of

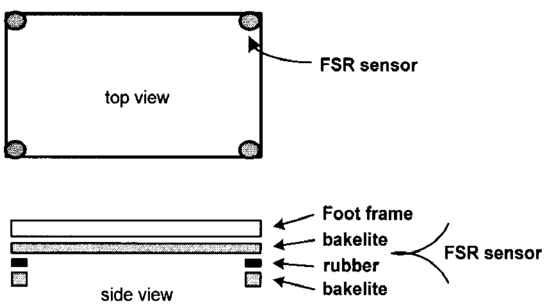


Fig. 6. Sole system.

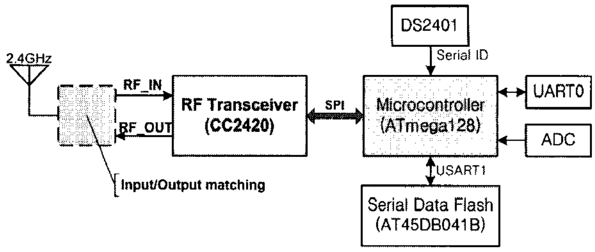


Fig. 7. Wireless sensor network system architecture.

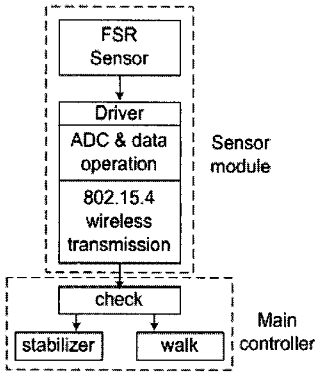


Fig. 8. Flowchart of sensor data.

a bakelite plate and a rubber plate. The sensors are fixed between the two plates.

The electric/electronic hardware of the sensor system is composed of a sensor driver, a transmitting board, and a receiving board. The sensor driver converts the sensor output into voltage, and analog data into digital data. The transmitting board transmits the ADC result of the sensor driver using wireless communication. The receiver receives the data and transmits the data to the main controller. Fig. 7 describes the sensor network system constructed on the robot, and Fig. 8 illustrates sensor data flow.

In this paper, a MICAZ wireless sensor network system from Berkely is deployed for communication of sensor data. The measured data from the FSR sensors are passed by the ADC and an amplification process, and are transmitted to the main controller. The main controller uses these data for the presumption of ground conditions and as controller input for the stabilization algorithm.

3.2. Simulation

In order to test the proposed stabilization algorithm, it is required to first conduct a simulation since the real experiment may possibly cause damage to the robot.

The robot walks according to a basic trajectory. In basic walking, a stride is 0.12m, velocity is 0.04m/s, and the ground is regarded as being flat. The robot steps on projected ground of 11mm in height with the toe of the swing leg. When the control algorithm is not applied, the sensor data is presented as given in Fig. 9. The robot pushes the ground continuously, and the heel does not contact until the end of the stride.

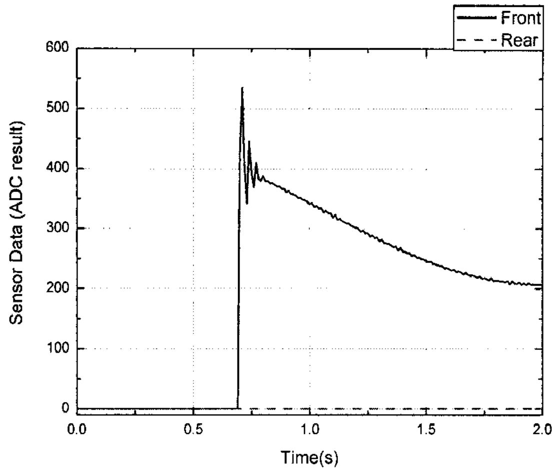


Fig. 9. FSR sensor data for uneven terrain.

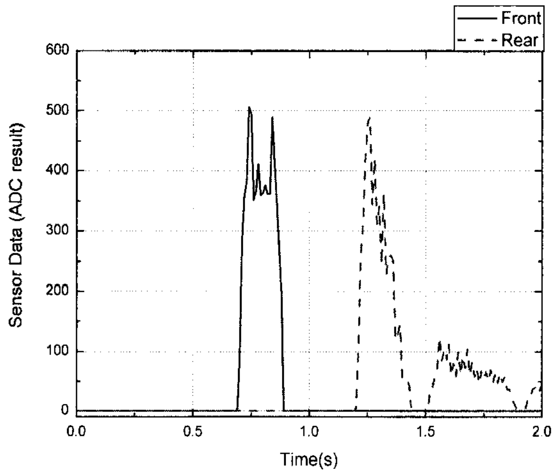


Fig. 10. Controller input for constant control.

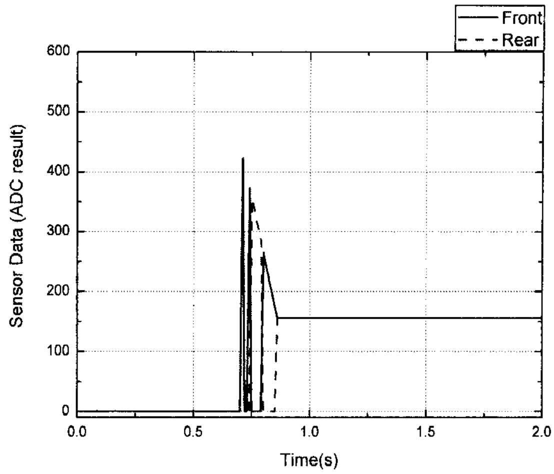


Fig. 11. Controller input for fuzzy control.

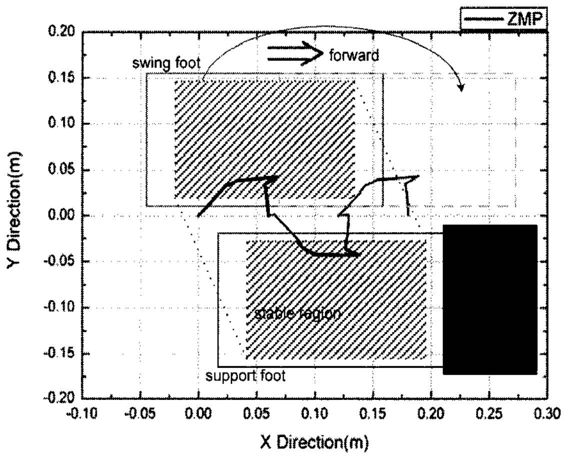


Fig. 12. ZMP of newly generated trajectory.

In the same situation, if the robot rotates the ankle joint by a constant value, the sensor data is the same as that given in Fig. 10. The toe of the swing leg contacts the ground at nearly 0.7 seconds, and departs at nearly 0.85 seconds. The heel of the swing leg contacts the ground at 1.2 seconds. This graph indicates that a fixed value for control cannot cope with various environments.

Because the toe or the heel can fail to maintain contact with the ground, stability is not guaranteed. This causes instability of the subsequent step.

Fig. 11 is a graph of the simulation results with application of the proposed control algorithm. After touching the ground, the toe and the heel repeat contact on the ground. The entire sole of the foot then contacts the ground after nearly 0.9 seconds.

When a unit step is ended, the robot generates a new trajectory for the changed posture and environment. The swing leg lands at an unexpected position by the control result of the previous step. Also, the angle of the ankle joint is different from the planned value. In the step of trajectory generation, the setting of the via-point applied by the changed situation is performed first. Next, in order to obtain smooth motion and prevent landing shock, the path trajectory of the end point of the foot is generated using the 5th polynomial. The inverse kinematics is used for each joint trajectory based on this path trajectory. After the trajectory for the next step is generated, the stability of the generated trajectory is verified by the ZMP stability criterion. The ZMP is operated through (2) and (3). If the stability of the trajectory is guaranteed, the robot resumes walking. If the trajectory is unstable, the robot waits for a new commands from the operator. Fig. 12 presents the ZMP of the new trajectory in the above simulation.

In Fig. 12 the x-axis signifies the saggital direction of the robot. The y-axis is the lateral direction of the robot. The ZMP is inside the stable region. Therefore the stability of the new trajectory can be confirmed through this graph.

3.3. Walking experiment

A walking experiment is performed under a similar situation to that employed for the simulation. Fig. 13 presents the measured sensor data for stepping on projected ground of 11mm in height with the toe of the swing leg. The toe contacts the ground nearly after 6 seconds and the ankle joint of the swing leg is controlled. The toe repeats contact and separation

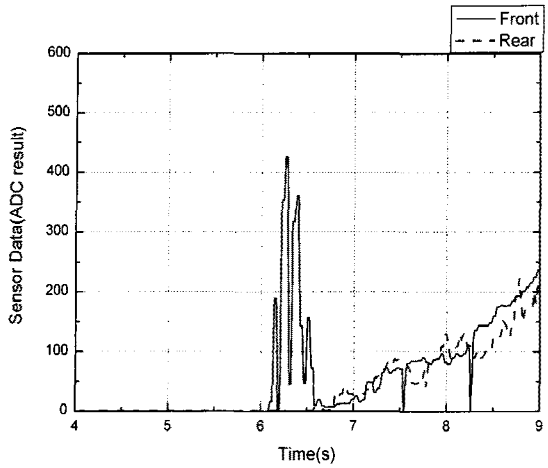


Fig. 13. Controller input for fuzzy algorithm when obstacle exists at a toe of a swing leg.

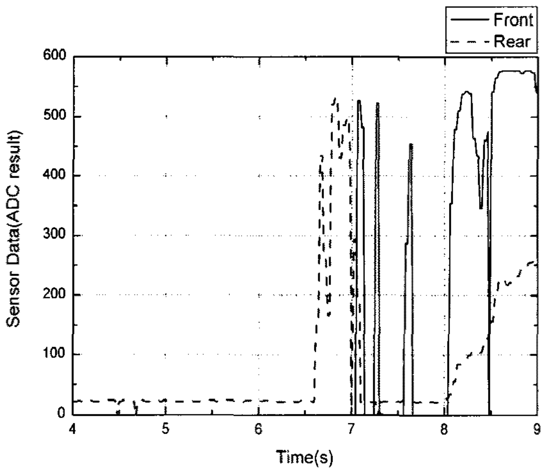


Fig. 14. Sensor data when an obstacle exists at the heel of a swing leg.

according to the result of the control. Both front sensor data and rear data are zero nearly 6.6 seconds owing to the difference in velocity between the original and controlled ankle joint rotation. The entire sole of the swing leg lands on the ground after nearly 7 seconds. The robot transfers the mass center to the center of two feet until 9 seconds, and the single step is ended.

Fig. 14 shows the measured sensor data for stepping on projected ground of 11mm in height with the heel of the swing leg. The heel contacts the ground after nearly 6.5 seconds and the ankle joint of the swing leg is controlled. The entire sole of the swing leg lands on the ground after nearly 7 seconds. The robot transfers the mass center to the center of two feet for 9 seconds, and the unit step is ended. The data from nearly 7 seconds to nearly 8 seconds is caused by vibration owing to a structural problem.

Fig. 15 is the controller output by the proposed algorithm. It presents variation per sampling time of the ankle joint. The positive value is that the toe of the foot is raised. When the toe contacts the projected ground, the control is ended at nearly 6.6 seconds by

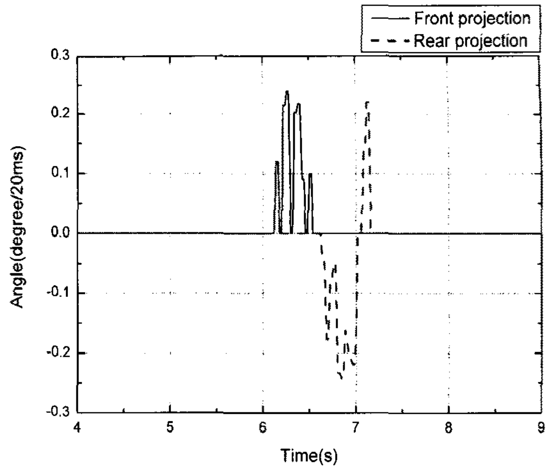


Fig. 15. Output angle from fuzzy algorithm.

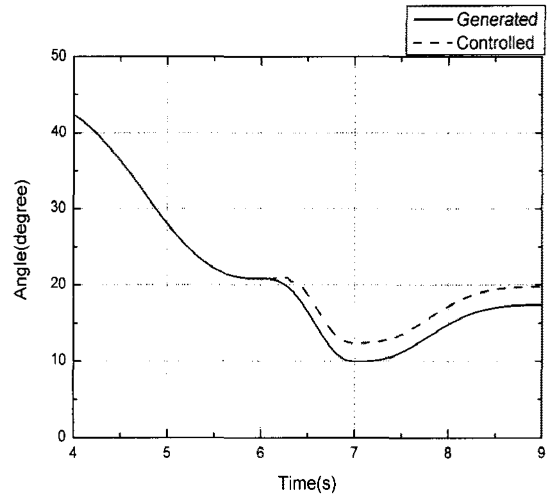


Fig. 16. Difference between the generated angle and the controlled one when obstacle exists at a toe of a swing leg.

the zero controller output. When the heel contacts the projected ground, the control is ended at nearly 7.2 seconds.

Figs. 16 and 17 present the controlled trajectory with operation of the robot. The difference in trajectory between the original and controlled trajectory ranges 6 to 6.5 seconds. This difference is maintained until 9 seconds, at which a single step is completed. It is confirmed by the graph that the control of the ankle joint is completed within the end of single step walking.

After the single step is finished, the generation of a new trajectory and verification of stabilization for the changed environment are similar to those for the previous simulation. At the end of walking, the foot has a posture as presented in Fig. 18. Fig. 18(a) shows the case where the proposed algorithm is not applied. The swing leg contacts the ground but the support leg does not maintain contact with the ground. In this case, the stability of the next step cannot be guaranteed. Fig. 18(b) reveals the case of application of the proposed algorithm. In this case, both the swing leg and support

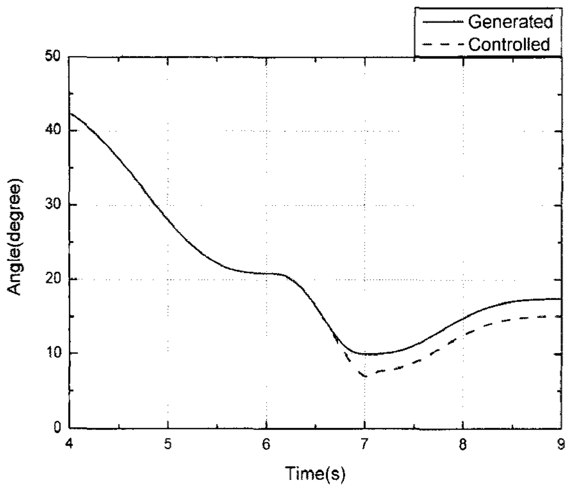
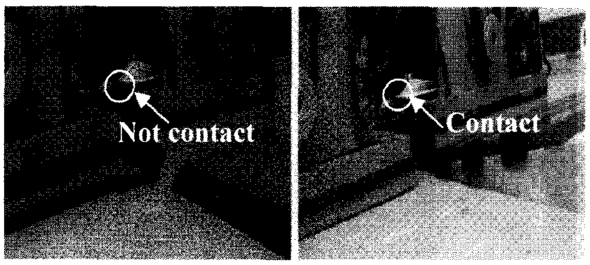


Fig. 17. Difference between the generated angle and controlled one when an obstacle exists at the heel of a swing leg.



(a) Not applied controller. (b) Applied controller.

Fig. 18. Comparison foot condition between controlled and uncontrolled case.

leg contact the ground as a result of control of the ankle joint. This not only confirms stable completion of the previous step but also is important for generation of stable trajectory for the subsequent step.

4. CONCLUSION

This paper proposed a real-time stabilization algorithm to realize the walking of a humanoid robot on uneven terrain. It was assumed that the ground condition on the basis of ground reaction forces measured by FSR sensors on the soles of the feet during walking. The robot could maintain balanced walking through control of the ankle joints using a fuzzy algorithm. After finishing a unit step walking, the robot generates a new trajectory concerning the changed situation, and this kind of walking can be resumed repeatedly as long as the stability of the new trajectory is verified by the ZMP criterion. The performance of the proposed algorithm is verified through an experiment using the humanoid robot ISHURO-II.

The proposed fuzzy system is based on the conventional fuzzy algorithm. Thus this algorithm might have only a low degree of noise, but it is also difficult to verify stability using the algorithm itself. So, different types of fuzzy algorithms will be considered, such as adaptive fuzzy algorithm and Takagi-Sugeno fuzzy algorithm, to stabilize a walking of a humanoid robot at uneven terrain. Furthermore, to walk more stably the researches of various sensors are needed. Especially, a gyroscope and accelerometer will assist the humanoid robot in maintaining stability when it walks. Also, a navigation algorithm is required for the humanoid robot because it will be needed to help the human in actual environments.

REFERENCES

[1] M. Vukobratovic and D. Juricic, "Contribution to the synthesis of biped gait," *IEEE Trans. on Bio-Medical Engineering*, vol. 16, pp. 1-6, 1969.

[2] K. Nishiwaki, S. Kagami, Y. Kuniyoshi, M. Inaba, and H. Inoue, "Online generation of humanoid walking motion based on a fast generation method of motion pattern that follows desired ZMP," *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and System*, vol. 3, pp. 2684-2689, 2002.

[3] D. Djoudi and C. Chevallereau, "Stability analysis of a walk of a biped with control of the ZMP," *Prof. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2461-2467, 2005.

[4] T. Sugihara and Y. Nakamura, "Whole-body cooperative balancing of humanoid robot using COG Jacobian," *Proc. of IEEE/RSJ. Intl. Conf. on Intelligent Robots and Systems*, pp. 2575-2580, 2002.

[5] D. Kim, S. Seo, and G. Park, "Zero-moment point trajectory modeling of a biped walking robot using an adaptive neuro-fuzzy system," *Proc. of IEE Control Theory*, vol. 152, pp. 411-426, 2005.

[6] T. Fukuda, Y. Komata, and T. Arakawa, "Stabilization control of biped locomotion robot based learning with GAs having self-adaptive mutation and recurrent neural networks," *Proc. of IEEE Int. Conf. on Robotics & Automation*, pp. 217-222, 1997.

[7] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, "Biped walking pattern generation by using preview control of zero-moment point," *Proc. of IEEE Int. Conf. on Robotics & Automation*, pp. 1620-1626, 2003.

[8] E. Cuevas, D. Zaldivar, and R. Rojas, "Incremental fuzzy control for a biped robot balance," *Proc. of IASTED Int. Conf. on Robotics and Applications*, pp. 99-104, 2005.

[9] Y. Okumura, T. Tawara, K. Endo, T. Furuta, M. Shimizu, "Realtime ZMP compensation for biped walking robot using adaptive inertia force control," *Proc. of IEEE/RSJ Intl. Conf. on*

Intelligent Robots and Systems, pp. 335-339, 2003.

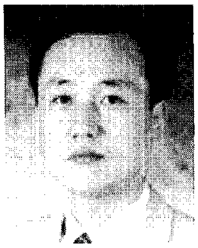
[10] K. Kondak and G. Hommel, "Online generation of stable gait for biped robots with feed-back loop algorithm," *Proc. of IEEE Conf. on Robotics, Automation and Mechatronics*, pp. 710-715, 2004.

[11] K. Nishiwaki, T. Sugihara, S. Kagami, M. Inaba, and H. Inoue, "Online mixture and connection of basic motions for humanoid walking control by footprint specification," *Proc. of IEEE Int. Conf. on Robotics & Automation*, pp. 4110-4115, 2001.

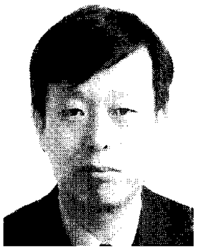
[12] Q. Huang and Y. Nakamura, "Sensory reflex control for humanoid walking," *IEEE Trans. on Robotics*, vol. 21, pp. 977-984, 2005.

[13] Y.-K. Hwang, K.-J. Choi, and D.-S. Hong, "Self-learning control of cooperative motion for humanoid robots," *International Journal of Control, Automation, and Systems*, vol. 4, no. 6, pp. 725-735, 2006.

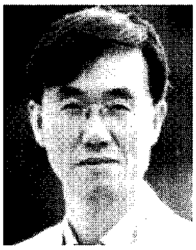
Jung-Shik Kong received the B.S. and Ph.D. degrees in Industrial Automation of Engineering from Inha University in 1998 and 2006, respectively. Since 2007, he has been with the Department of the Micro Robot at Daeduck College, where he is currently a Professor. His research interests include humanoid robots, intelligent control, robust control, and biomedical engineering.



Eung-Hyuk Lee received the B.S. and Ph.D. degrees in Electronic Engineering from Inha University in 1985 and 1992, respectively. Since 2000, he has been with the Department of Electronic Engineering at Korea Polytechnic University, where he is currently a Professor. His research interests include service robot control, mobile healthcare systems, image processing, and industrial control.



Bo-Hee Lee received the B.S. in Electronic Engineering from Inha University in 1985 and the Ph.D. degree in Mechanical Engineering from Inha University in 1996. Since 2000, he has been with the Department of Electrical Engineering in Semyung University, where he is currently a Professor. His research interests include walking robots, intelligent control, and mobile robots.



Jin-Geol Kim received the B.S. in Electronic Engineering from Seoul National University in 1978 and the Ph.D. degree in Electrical and Computer Engineering from the University of Iowa in 1988. He is currently a Professor of Electrical Engineering in Inha University. His research interests include nonlinear control, walking robots, and intelligent robots.