안정적인 보행을 위한 이족 휴머노이드 로봇에서의 서포트 벡터 머신 이용

Use of Support Vector Machines in Biped Humanoid Robot for Stable Walking

김 동 원, 박 귀 태*
(Dongwon Kim and Gwi-Tae Park)

Abstract : Support vector machines in biped humanoid robot are presented in this paper. The trajectory of the ZMP in biped walking robot poses an important criterion for the balance of the walking robots but complex dynamics involved make robot control difficult. We are establishing empirical relationships based on the dynamic stability of motion using SVMs. SVMs and kernel method have become very popular method for learning from examples. We applied SVM to model the practical humanoid robot. Three kinds of kernels are employed also and each result has been compared. As a result, SVM based on kernel method have been found to work well. Especially SVM with RBF kernel function provides the best results. The simulation results show that the generated ZMP from the SVM can be improve the stability of the biped walking robot and it can be effectively used to model and control practical biped walking robot.

Keywords : support vector machines, humanoid robot, stable walking, zero moment point

I. Introduction

Building machines with humanlike form is not only an interesting scientific challenge, but also a practical engineering endeavor. With a physical form similar to humans, the humanoid robots are potential tools to be used as proxies or assistants of humans in performing tasks in the real world environments which are including rough terrain, steep stairs, and obstacles. Humanoid robots have recently evolved into an active research area with the creation of several humanoid robot systems and many related issues such as stability criterion, actual robot design and application, and dynamics analysis have been studied [1-4]. In addition, the humanoid robots involve many technical issues to be solved. Among these issues a stable and reliable biped walking is the most fundamental and yet unsolved with a high degree of reliability.

It is generate dynamically consistent walking patterns [5]. So the quest for a fully autonomous humanoid robot is a main scientific goal of the artificial intelligence community [6-8].

The current research is directed toward the generation of anthropomorphic trajectories, and toward efficient ways for the biped robot to control them. The robot is fitted with feet equipped with sensors measuring the ground-foot forces, in order to exploit the concepts of zero moment point (ZMP) [9].

The ZMP was originally defined for ground contacts of legs by Vukobratovic [10-11] as the point in the ground plane about which the total moments due to ground contacts become zero in the plane. As long as gravity forces govern walking gaits, the ZMP will be a significant dynamic equilibrium criterion. As a result the ZMP trajectories are used as a reference of humanoid robot for stable walking. Recently a few attempts have been made to develop human-like walking as modeling desired ZMP trajectory. Kim *et al.* [12-13] proposed a method to generate smooth walking pattern using fuzzy and adaptive neuro-fuzzy systems and their results are original and unconventional. This is mainly due to relatively high predictive ability of fuzzy systems as demonstrated by a comparison with statistical regression counterparts [13]. However, there still exist other intelligent systems like support vector machines not yet evaluated. Investigating their applicability to humanoid robot is highly demanded since it may exhibit better predictive ability than typical fuzzy systems, thereby providing more improved insight into human-like walking mechanisms.

In this study, support vector machines (SVM) are first applied to model a ZMP trajectory of practical humanoid robot and their performance can be considerably varied depending on the type of kernels adopted by the networks. As a function of three kinds of kernel, the SVM performance is optimized. The SVM model is compared to the fuzzy system and classical statistical regression models.

II. Biped humanoid robot for experiments

In practice, we have designed and implemented a biped humanoid robot as shown in Fig. 1. The robot has 19 joints and the locations of the joints during motion are also shown in Fig. 1. The height and the total weight are about 308mm and 1700g including batteries. Each joint is driven by the RC servomotor that consists of a DC motor, gear, and simple controller. Each of the RC servomotors is mounted in the link structure. Our biped walking robot is able to walk under the condition which one step is 48 mm per 1.4 s on the flat floor.

As a significant stability criterion, ZMP trajectory is used and real ZMP is calculated based on the data of the force sensors equipped on each foot. In addition, it is experimented

* 책임저자(Corresponding Author)
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김동원, 박귀태 : 고려대학교 전기전자전파공학부
(upground@korea.ac.kr/gtpark@korea.ac.kr)
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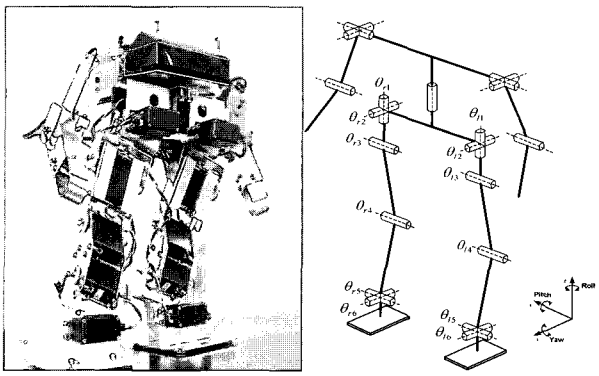


그림 1. 실제 휴머노이드 로봇과 관절표현.
Fig. 1. Actual humanoid robot and its joint angle representation.

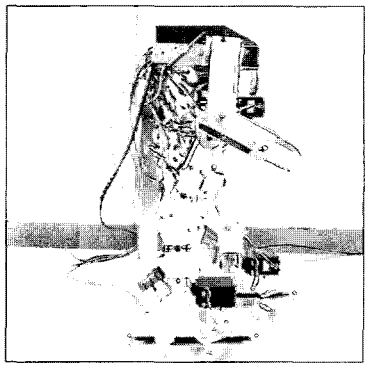
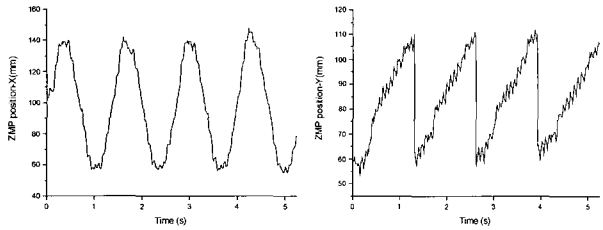
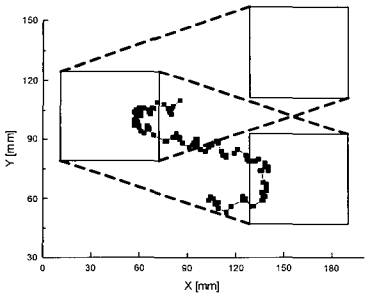


그림 2. 평지에서의 이족휴머노이드 로봇의 보행.
Fig. 2. Biped humanoid robot walking on the flat ground.



(a) x-coordinate (b) y-coordinate



(c) ZMP trajectory

그림 3. 실제 ZMP 와 휴머노이드 로봇의 궤적(평지).
Fig. 3. Real ZMP positions and corresponding trajectory of biped humanoid robot (flat ground).

and obtained from various grounds such as flat ground and slope. More detailed information about specification and block diagram of the robotic system are in [12-13].

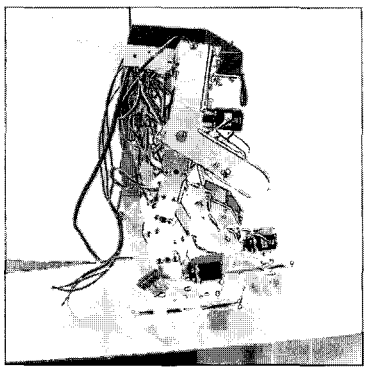
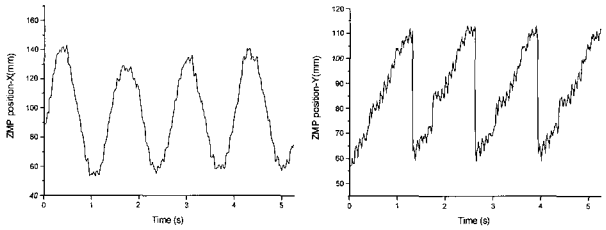
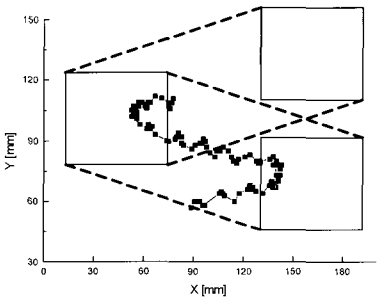


그림 4. 언덕에서의 이족휴머노이드 로봇의 보행.
Fig. 4. Biped humanoid robot walking on the slope.



(a) x-coordinate (b) y-coordinate



(c) ZMP trajectory

그림 5. 실제 ZMP 와 휴머노이드 로봇의 궤적(언덕).
Fig. 5. Real ZMP positions and corresponding trajectory of biped humanoid robot (slope).

The walking motions of the robot walking on the flat ground are shown in Fig. 2. When the humanoid robot walks on the flat ground, the real ZMP positions, x-coordinate and y-coordinate, and their corresponding ZMP trajectories are also shown in Fig. 3, respectively. Fig. 4 depicts the walking motion of the humanoid robot when it is walking up a 10° slope. In addition, Fig. 5 shows the real ZMP positions and their corresponding trajectory.

The complex dynamics involved in the biped walking robot make robot control a challenging task. So if the highly nonlinear and complex dynamics are modeled well, it is possible to explain empirical laws by incorporating them into the biped walking robot. We used support vector machines to be studied in next section to present the nonlinearities using the actual ZMP trajectories.

III. Support vector machines for stable walking patterns

The SVMs can be applied to regression problems by the

introduction of an alternative loss function [15-16]. The basis idea in support vector regression (SVR) is to map the input data x into a higher dimensional feature space via a nonlinear mapping Φ and then a linear regression problem is obtained and solved in this feature space. The following presents some basic concepts of SVR as described by prior research. A detailed explanation may be found in [14-16]. In SVM method, the regression function is approximated by the following function:

$$y = \sum_{i=1}^{l} w_i \Phi_i(x) + b \tag{1}$$

where $\{\Phi_i(x)\}_{i=1}^{l}$ are the feature of inputs, $\{w_i\}_{i=1}^{l}$ and b are coefficients. The coefficients are estimated by minimizing the regularized risk function.

$$R(C) = C\frac{1}{l}\sum_{i=1}^{l} L_\varepsilon(d_i, y_i) + \frac{1}{2}\|w\|^2 \tag{2}$$

Where

$$L_\varepsilon(d_i, y_i) = \begin{cases} 0 & for \quad |d-y| < \varepsilon, \\ |d-y| - \varepsilon & otherwise \end{cases} \tag{3}$$

and ε is a prescribed parameter.

In Eq. (2), $L_\varepsilon(d_i, y_i)$ is ε-insensitive loss function, which indicates that it does not penalize errors below ε. $\frac{1}{2}\|w\|^2$ is used as a flatness measurement of Eq. (1) and C is a regularized constant determining the tradeoff between the training error and the model flatness. Introduction of slack variables ζ, ζ^* leads Eq. (2) to the following constrained function

$$Minimize \quad R(w, \zeta^*) = \frac{1}{2}\|w\|^2 + C^*\sum_{i=1}^{l}(\zeta_i + \zeta_i^*) \tag{4}$$

$$\begin{aligned} s.t. \quad & w\Phi(x_i) + b - d_i \le \varepsilon + \zeta_i, \\ & d_i - w\Phi(x_i) - b \le \varepsilon + \zeta_i^*, \quad \zeta_i, \zeta_i^* \ge 0. \end{aligned} \tag{5}$$

Thus, function (1) becomes the explicit form

$$\begin{aligned} f(x, \alpha_i, \alpha_i^*) &= \sum_{i=1}^{l} w_i \Phi_i(x) + b = \sum_{i=1}^{l}(\alpha_i - \alpha_i^*)\Phi(x_i)^T\Phi(x) + b \\ &= \sum_{i=1}^{l}(\alpha_i - \alpha_i^*)K(x_i, x) + b \end{aligned} \tag{6}$$

In formula (6), Lagrange multipliers α_i and α_i^* satisfy the constraints $\alpha_i * \alpha_i^* = 0$, $\alpha_i \ge 0$, $\alpha_i^* \ge 0$ and they can be obtained by maximizing the dual form of function (5)

$$\begin{aligned} \Phi(\alpha_i, \alpha_i^*) = & \sum_{i=1}^{l} d_i(\alpha_i - \alpha_i^*) - \varepsilon\sum_{i=1}^{l}(\alpha_i + \alpha_i^*) \\ & - \tfrac{1}{2}\sum_{i=1}^{l}\sum_{j=1}^{l}(\alpha_i - \alpha_i^*)(\alpha_j - \alpha_j^*)K(\alpha_i, \alpha_j) \end{aligned} \tag{7}$$

with constraints

$$\sum_{i=1}^{l}(\alpha_i - \alpha_i^*) = 0, \quad 0 \le \alpha_i \le C, \ 0 \le \alpha_i^* \le C \tag{8}$$

Based on the nature of quadratic programming, only a number of coefficients among α_i and α_i^* will be nonzero, and the data points associated with them refer to support vectors. The form $\Phi(x_i)^T\Phi(x)$ in Eq. (6) is replaced by kernel function with the form

$$K(x, y) = \Phi(x)^T\Phi(y) \tag{9}$$

There are some different kernels for generating the inner products to construct machines with different types of nonlinear decision surfaces in the input space. We employed three kinds of kernel functions as follows

$$\begin{aligned} & linear: && K(x, y) = x^T y \\ & polynomial: && K(x, y) = (xy + 1)^d \\ & RBF: && K(x, y) = \exp(-\tfrac{1}{\sigma^2}\|x - y\|^2) \end{aligned} \tag{10}$$

Using the three types of kernel functions such as linear, polynomial, and radial basis function for SVR, approximated models are constructed and their results are compared. The accuracy was quantified in terms of mean squared error (MSE) values. The SVR was applied to model the ZMP trajectory of the humanoid robot depicted in previous section using actual ZMP data. In Table 1, MSE values corresponding three types of kernel functions are listed when the humanoid robot is walking on the flat ground. And we can compare the results with respect to various kernel functions.

One of the advantages of linear kernel is that there is no parameter to tune except the constant C. For the nonlinear case there is an additional parameter, the kernel parameter, to tune. As constant C, we set the value as 1000. Moreover, the degree of polynomial and width of RBF are set to 2.

From the Table 1, the polynomial kernel provides worse results than the RBF kernel. In addition, it takes a longer time in the procedure. The generated ZMP positions from the RBF kernel, and its errors between actual data and generated data are shown in Fig 6. In the figure, we can also see the corresponding ZMP trajectories that are generated from the RBF kernel and error distribution which is information for state and range of each position error. From the figure, the generated ZMP is very similar to actual ZMP trajectory of the biped humanoid robot.

A series of comprehensive experiments was conducted again and the results are summarized in the same way as before. Other results from SVR about humanoid robot walking on the slope are shown in Table 2. As seen in the results, the SVR with RBF kernel has the best results among other kernel functions. Similarly as in the two cases of the walking condition, flat ground and slope, the RBF kernel function has considerably

표 1. 커널함수와 휴머노이드 로봇의 정밀도.

Table 1. Kernel functions and corresponding accuracy of humanoid robot (0°).

kernel type	x-coordinate	y-coordinate
linear	47.184	60.704
polynomial	9.695	18.568
RBF	2.524	2.721

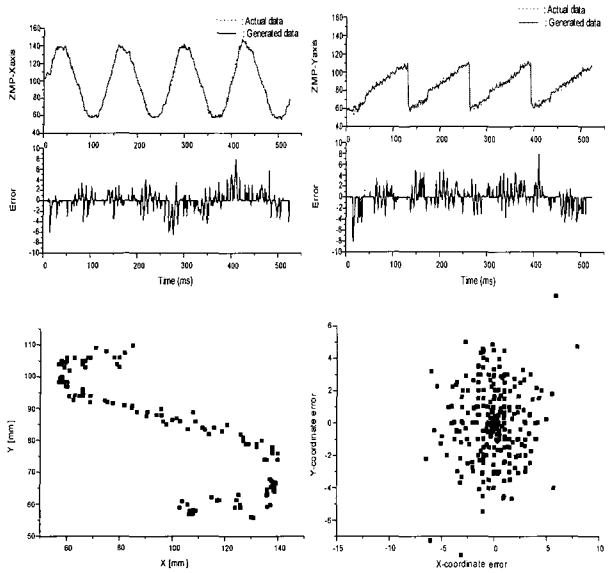


그림 6. 생성된 ZMP 위치와 휴머노이드 로봇의 궤적.

Fig. 6. Generated ZMP positions and corresponding trajectory of biped humanoid robot (0°).

표 2. 커널함수와 휴머노이드 로봇의 정밀도.

Table 2. Kernel functions and corresponding accuracy of humanoid robot(10°).

kernel type	x-coordinate	y-coordinate
linear	48.28	58.648
polynomial	15.313	18.287
RBF	6.938	3.732

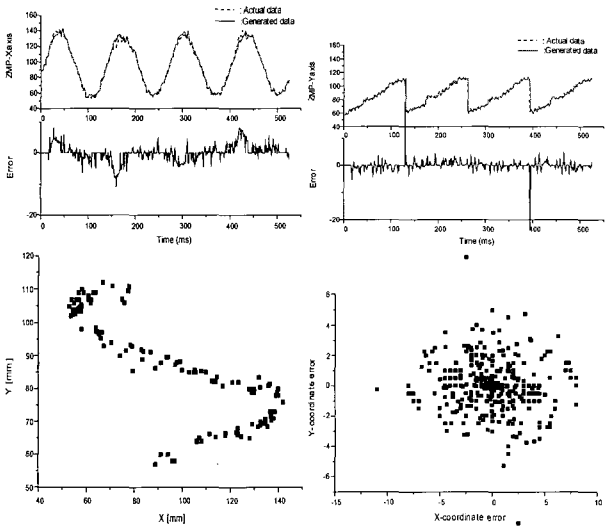


그림 7. 생성된 ZMP 위치와 휴머노이드 로봇의 궤적.

Fig. 7. Generated ZMP positions and corresponding trajectory of biped humanoid robot (10°).

best results. As a result, the SVR with RBF structures defined for the two cases are most likely to yield the best model for the stable walking of humanoid robot.

Fig. 7 shows the generated ZMP positions and their trajectory from SVR with RBF kernel. In the figure, each position and its errors are illustrated. Moreover, the ZMP trajectory corresponding generated positions and its error distributions are also shown, respectively.

표 3. 다른 모델과의 성능비교.

Table 3. Comparison results with other methods.

Methods	ground condition	x	y
Regression model [13]	flat	7.780	13.558
Fuzzy system [12,13]		4.164	4.763
		4.249	4.59
SVR		2.524	2.721
Regression model [13]	slope	13.661	15.560
Fuzzy system [12,13]		8.552	5.011
		8.862	6.443
SVR		6.938	3.732

To show the excellent performance demonstrated by the SVR, we compare the performance with other methods. Table 3 provides comparisons with other techniques being already proposed in the literature. The comparison is realized on the basis of the same performance index for the actual ZMP trajectory. It is obvious that the SVR model outperforms other models so the SVR can be effectively used to model and control complex human-like walking mechanism.

VI. Conclusions

This paper deals with support vector regression modeling of zero moment point (ZMP) trajectory of a practical biped walking robot. The trajectory of the ZMP poses an important criterion for the balance of the walking robots but complex dynamics involved make robot control difficult.

To establish empirical relationships between process parameters and to explain empirical laws by incorporating them into the biped walking robot, SVM is applied to model the ZMP trajectory data. Real ZMP data throughout the whole walking phase are obtained from the real biped walking robot on the flat floor and some slopes. Three kinds of kernels are employed and each result has been compared. As a result, SVM based on kernel method have been found to work well. Especially SVM with RBF kernel function provides the best results. The simulation results show that the generated ZMP from the SVM can be improve the stability of the biped walking robot and SVM can be effectively used to model and control practical biped walking robot.

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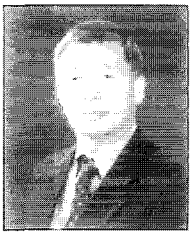
김 동 원

1974년 3월 15일생. 2002년~현재 고려대학교 전기공학과 박사수료. 관심분야는 이족 휴머노이드 로봇 설계 및 이의 지능 모델링, 소프트 컴퓨팅기반 진화된 뉴로-퍼지 시스템, 지능제어, GMDH-type 알고리즘.



박 귀 태

1947년 10월 25일생. 1981년~현재 고려대학교 전기공학과 교수. 2000년~현재 (사) IBS KOREA 회장. 관심분야는 진화된 퍼지 및 신경망, 휴머노이드 로봇 및 모바일 로봇, 컴퓨터 비전, 지능제어, 인텔리전트 빌딩시스템 및 정보통신.