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Performance Index-Based Evaluation of Quadruped Robotic Walking Configuration

Byoung-Ho Kim

**Bio-Mimetic Control & Robotics Lab., Dept. of Mechatronics Eng., Kyungsung Univ.,
Busan, 608-736, Korea**

Abstract

This paper presents a performance index-based evaluation for a better quadruped robotic walking configuration. For this purpose, we propose a balance-based performance index that enables to evaluate the walk configuration of quadruped robots in terms of balance. In order to show the effectiveness the proposed performance index, we consider some types of walking configurations for a quadruped robotic walking and analyze the trend of the proposed performance index in those quadrupedal walking. Through the simulation study, it is shown that an effective walk configuration for a quadrupedal walking can be planned by adopting the proposed performance index.

Key Words : Performance index, Balance, Walking configuration, Quadruped robots.

1. Introduction

Mobile robots are useful for performing various services at industrial work spaces, hospitals, exhibition halls, homes, and so on. So, many research groups are studying on the mechanism, motion planning, and control methods for their applications. In general, locomotion can be considered as an additional function for the completion of various mobile manipulation tasks. Thus, a locomotion mechanism that enable a mobile robot to move throughout its environment is very important in the design aspect of mobile robots. Actually, there are various types of mobile robots developed in world wide. Those mobile robots can be classified as three types of locomotion mechanisms [1]: wheel-based, legged, and hybrid of the two mechanisms. They have individual features by employing different locomotion mechanisms. Specifically, a wheel-based mobile robot is very useful to do delivery services on flat ground [2]. In fact, the wheeled locomotion is more efficient than the legged locomotion on flat surfaces. However, a legged walking robot is more adaptable in a rough terrain, relatively [3]. The hybrid type of mobile robot can utilize the advantages of wheel and leg mechanisms [4] [5].

Especially, a walking robot is very recommended to do a task passing through a stairway or some obstacles [6] [7]. It is because the legged locomotion is capable of overcoming such inconveniences. Of course, complexity of the mechanism may be increased when a robot has several legs. If any leg of the robot is not compatible with others motion, the maneuverability and/or equilibrium of the robot may not be guaranteed. So, coordination of each leg is very important to achieve the desired walking performance. In order to walk, a robot must lift its leg in what order. Thus, it is required to consider an effective gait pattern for reliable walking. A proper walking strategy for all legs is also needed. For a more balanced walking, the walk configuration of the robot is to be well-planned through the evaluation of each footstep in real time. In this sense, we need to consider a performance index that is useful for identifying the configuration of multi-legged walking. Related to a performance index for multi-legged robots, a stability margin concept was presented for static quadrupedal creeping gaits [8], and the energy-based stability margin was also used for legged walking robots [9] [10]. However, a performance index for multi-legged walking in terms of balance is rare yet.

The objective of this paper is to present a performance index-based evaluation for a better quadruped robotic walking configuration. To do that, we propose a balance-based performance index which is useful for evaluating different walk configurations. Through simulation studies, it is shown that an effective walk configuration of a quadrupedal robot can be evaluated by using the proposed performance index. This paper is organized as follows. In Section 2, we specify a simplified model of quadruped robotic walking. A balance-based performance index for the evaluation of a walk configuration is described in Section 3. In Section 4, simulation results for an exemplary quadrupedal walk-

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Corresponding Author : kimbh@ks.ac.kr (Byoung-Ho Kim)

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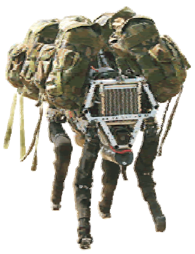
ing are shown to illustrate the feature of the proposed performance index. Finally, concluding remarks are given in Section 5.

2. Model of Quadruped Robots and Walking Patterns

In order to consider the walking of quadrupedal robots, let us observe some representative four-legged walking mechanisms as shown in Fig. 1. For example, Fig. 1(a) shows a real dog who is available for hunting, searching and protecting something needed to his master. An industrial company, Sony in Japan, developed an entertainment robotic dog shown in Fig. 1(b) [11] [12]. Recently, some researchers have an interest in the robots for military applications [13]. The robot in Fig. 1(c) was developed for the purpose of military delivery services by Boston Dynamics Company [14]. Actually, this kind of quadruped robot is useful for delivering some loads required in dangerous environment including an irregular terrain.

(a) A Korean Jindo Dog

(b) An entertainment robot, AIBO



(c) A military service robot, BigDog

Fig. 1 Quadrupedal walking mechanisms.

To deal with such a quadrupedal walking, this paper considers a typical four-legged locomotion mechanism shown in Fig. 2 as a simple walking model. We especially concern on the foot configuration formed by the locations of feet. In general, the foot configuration of a multi-legged robot depends on the number of leg and their gait pattern. If a mobile robot has k legs, the number of possible gaits is $(2k-1)!$, where the symbol ! means a factorial expression [1]. In particular, a quadrupedal robot can make 5040 gaits. So, there exists so many styles of walking pattern. Nevertheless, the balance of such a quadrupedal robot may be unstable in a walking process according to the locations of supporting feet [15] [3]. On the other hand, the case of a six-legged robot is flexible comparably to make various foot configurations for stable walking [16] [17]. But its control is rather hard due to the structural complexity. Thus, planning a proper foot configuration is very important to improve the performance of the quadrupedal walking.

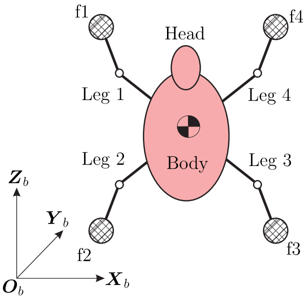


Fig. 2 Model of a quadrupedal robot.

Related to the walking patterns of multi-legged robots, many researchers have been trying to know which walking style is adequate for a legged locomotion [8] [13] [18] [19]. For instance, the quadrupedal walking patterns in a sequential fashion can be classified as Table 1. Such a walking pattern can be used properly according to the given environmental condition and a special footstep motion.

Table 1. Quadrupedal walking patterns in a sequential fashion starting from the first leg.

Case	Order of foot step	Remarks
I	f1 → f2 → f3 → f4 → f1	See Fig. 2
II	f1 → f2 → f4 → f3 → f1	
III	f1 → f3 → f4 → f2 → f1	
IV	f1 → f3 → f2 → f4 → f1	
V	f1 → f4 → f2 → f3 → f1	
VI	f1 → f4 → f3 → f2 → f1	

3. Balance-Based Performance Index

If a quadruped robot lifts a leg in order to walk, the other three legs should support the body for the walking. In such a walking situation, it is very important to consider the balance of the walking system. In fact, a quadruped robot is usually able to stand easily on four feet, but its balance may be uncertain as one of feet is lifted in the process of walking. For a walk without falling, it is useful to think about the movement of the center of gravity(COG) of the robot system as shown in Fig. 3. A robot system may be in a stable posture if the COG is possible to be replaced to the equilibrium position of the robot system during walking.

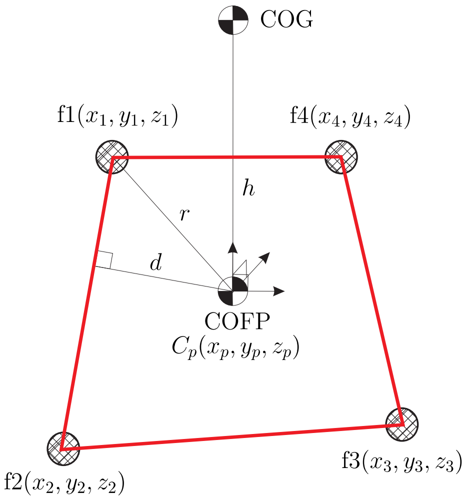


Fig. 3 Center of gravity and centroid of a foot polygon.

In fact, if the COG has been adjusted and projected to the centroid of foot polygon(COFP), the walking configuration can be placed in an equilibrium posture. But its grade of balance and stability may be different according to the shape of the polygon and the height between the position of the COFP and the COG. Thus, it is acceptable usually that the more the shape and the height are spacious and low respectively, the more the walking balance becomes better. In this sense, this paper proposes a performance index to estimate different walking configurations as follows.

$$I_{BS} = (\text{SGN}) d_{min}(t) r_{min}(t) e^{-h(t)} \tag{1}$$

where $d_{min}(t)$ is the minimum distance between the COFP and the line pass through the two neighbor's feet positions. The parameter $r_{min}(t)$ is the minimum distance between the COFP and each foot position. The $h(t)$ denotes the perpendicular distance of the COG into the COFP. Physically, these parameters can be considered as the stability margin, the balance margin, and the potential margin based on the center of gravity of multi-legged robot systems, respectively. If SGN is positive, the COFP is located inside of the polygon, while the position of the COFP is outside of the polygon when it is negative. So, it can be used as an estimating condition for the relative stability of any foot configuration. In particular, the parameter SGN is determined by

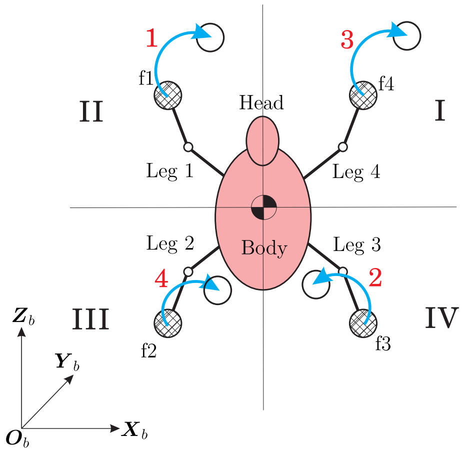
$$\text{SGN} = \begin{cases} -1 & : \; S_1 > S_2 \\ 0 & : \; S_1 = S_2 \\ 1 & : \; S_1 < S_2 \end{cases} \tag{2}$$

where S_1 denotes the area of the polygon formed by the position of the COFP and the supporting feet and S_2 is the area of the polygon formed by the supporting feet.

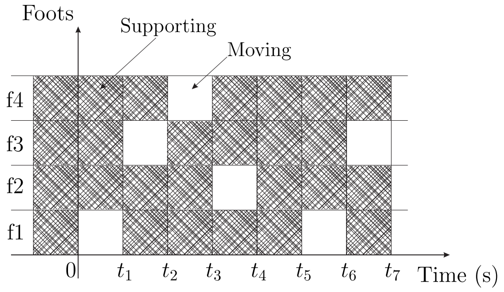
Practically, the performance index I_{BS} in (1) provides the minimum value of each foot configuration for a given walking task. Thus we can guess the functional attraction level of any foot configuration from the index. It is finally evaluated that the walk configuration with the largest value of the index is preferred in a comparative study considering many walking styles.

4. Quadrupedal Walking Simulation

This section shows the simulation results of an exemplary quadrupedal walking task to confirm the effectiveness of the performance index presented in Section 3.



(a) Gait sequence

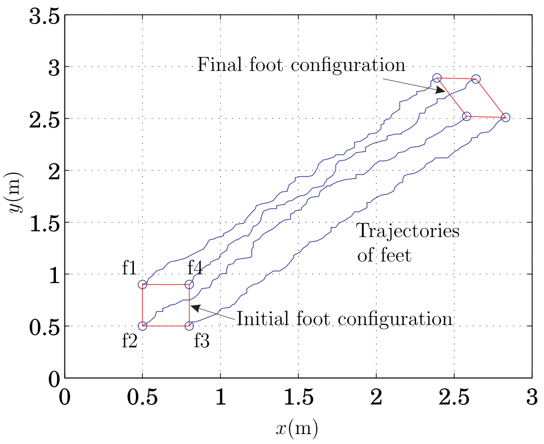


(b) Gait diagram

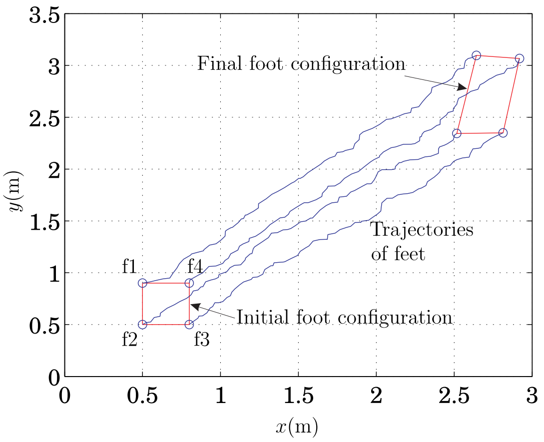
Fig. 4 Walking pattern of a quadrupedal robot.

In order to assign a proper walking pattern for the simulation, we pay attention to the recent study tried to find out a reasonable gait sequence for quadrupedal robots [20]. In the research, a creeping gait sequence that the order of the moving leg is assigned as the third case in Table 1 was confirmed as a useful walking pattern for quadrupedal robots in terms of walking balance. In fact, it is observed empirically that the real dog shown in Fig. 1(a) walks normally by such a creeping gait style. This situation is also usually observed in a baby's crawling motion. So, we considered the sequential creeping gait style as shown in Fig. 4 to identify the significance of the performance index.

For comparative analysis of the quadrupedal walking in Fig. 4, our approach is firstly to check the performance index for any reference walking trajectory under the condition that the center of gravity of the robot has been adjusted and projected to the centroid of foot polygon at each step. Next concern is to analyze the corresponding foot configuration based on the profile of the performance index.



(a) Case 1



(b) Case 2

Fig. 5 Reference foot trajectories for the walking task.

For the simulation study, two reference walking trajectories with 100 steps for a respective foot have been predefined as shown in Fig. 5. Those reference trajectories were actually made by a random process as follows:

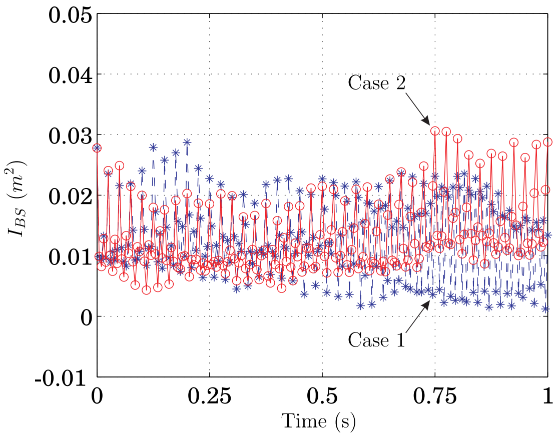
$$x_i(t+dt) = x_i(t) + p_i\{\text{rand}(1)\},\ i = 1, 2, \cdots, 4 \qquad (3)$$

$$y_i(t+dt) = y_i(t) + p_i\{\text{rand}(1)\},\ i = 1, 2, \cdots, 4 \qquad (4)$$

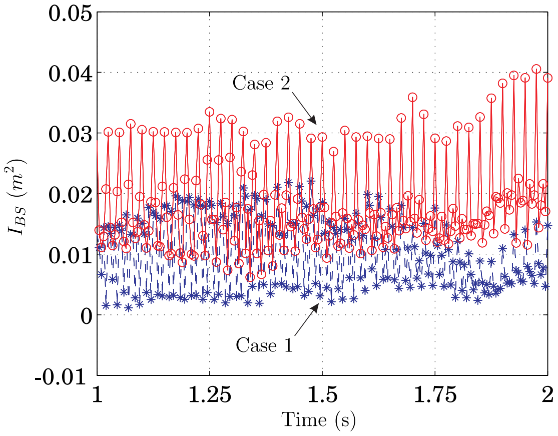
where $\text{rand}(1)$ is a random function to generate an arbitrary value in between 0 and 1. The p_i plays a role to adjust the pace of walking, and it was set to 0.05. The parameter dt indicates the sampling time for each step motion of a moving leg, and it was set to 5 ms. For convenience, we assumed that the height of the COG can be maintained at a constant position, 0.3 m, and also the position of the actual COG can be moved into the inside of each foot polygon. The walking motion of the robot shown in Fig. 2 was specified in planar space. The initial positions of each foot are specified in Table 2.

Table 2. Initial positions of four feet.

Foot	x position(m)	y position(m)	z position(m)
f1	0.5	0.9	0
f2	0.5	0.5	0
f3	0.8	0.5	0
f4	0.8	0.9	0

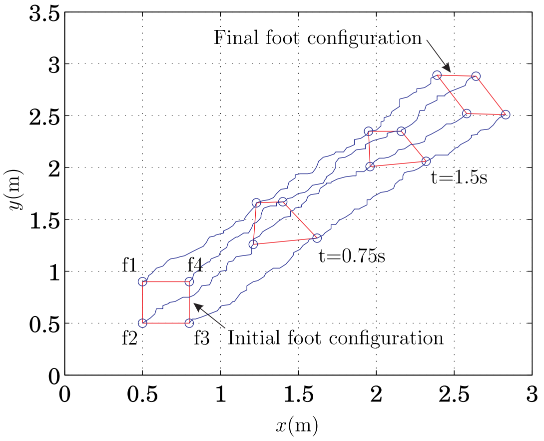


(a) I_{BS} for t = 0 ∼ 1.0 s

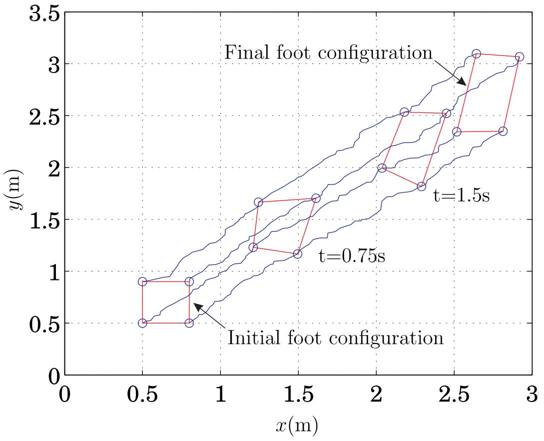


(b) I_{BS} for t = 1.0 ∼ 2.0 s

Fig. 6 Profiles of the performance index for the two cases of walking, where '$\circ$,' or '$*$' represents the check time for each performance.



(a) Case 1



(b) Case 2

Fig. 7 Exemplary foot configurations for the two cases of walking.

Fig. 6 shows the trend of the performance index, I_{BS} in (1), for each walking task predefined as the two cases in Fig. 5. As a result, the actual performance indices for the two cases are similar in level until 0.75 s, but after that their profiles are different, and the level of the case 2 is generally more larger. This implies that the walking configuration of the second case is more balanced and stabled than that of the first case. This analysis is also confirmed from Fig. 7 that compares some foot configurations extracted in the walking process of the two cases. It is actually observed that the foot polygons in Fig. 7(b) are more balanced in shape. From the simulation, it is reversely pointed out that the performance index proposed in this paper can be used to find a reliable and attractive foot configuration during a multi-legged walking process.

On the other hand, according to the practical environment that a legged robot meets, any footstep of the robot may be evaluated in a reasonable region repeatedly and/or irregularly for a particular gait motion. Actually, this situation can be observed in the walking pattern for a dog to search something in a rough terrain. In this case, the proposed performance index is available for determining an effective foot position for the given task in terms of balance. Such a footstep planning is actually useful for effective delivery services as shown in Fig. 1(c). In order for the optimal walking, a proper combination with some other indices [8]- [10] is additionally desirable.

5. Conclusions and Future Works

This paper presented a performance index-based evaluation for a better quadruped robotic walking configuration. In order to evaluate any walk configuration of quadruped robots, a balance-based performance index has been proposed. Through simulations for two exemplary reference trajectories, the feasibility of the proposed index was proven. As a result, it is concluded that a good walk configuration for quadrupedal walking can be identified by adopting the proposed evaluation process and thus more effective quadrupedal walking can be planned in the viewpoint of walking balance. Since this effort is actually related to the determination of any footstep to make a well-balanced walk configuration, the current study is consequently available for dextrous locomotion of multi-legged robots.

In addition, adaptive footstep planning based on a proper combination of multiple indices will be an interesting research topic for various legged mobile manipulations.

References

[1] R. Siegwart and I. R. Nourbakhsh, *Introduction to autonomous mobile robots*, The MIT Press, 2004.

[2] Y. Hada, H. Gakuhari, K. Takase, and E. I. Hemeldan, “Delivery service robot using distributed acquisition, actuators and inteliigence,” *in Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2004, pp. 2997-3002.

[3] J. Estremera and P. G. deSantos, “Generating continuous free crab gaits for quadruped robots on irregular terrain,” *IEEE Transactions on Robotics*, vol. 21, no. 6, 2005, pp. 1067-1076.

[4] S. Nakajima, E. Nakano, and T. Takahashi, “Motion control technique for practical use of a leg-wheel robot on unknown outdoor rough terrains,” *in Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2004, pp. 1353-1358.

[5] M. Takahashi, K. Yoneda, and S. Hirose, “Rough terrain locomotion of a leg-wheel hybrid quadruped robot,” *in Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2006, pp. 1090-1095.

[6] U. Saranli, M. Buehler, and D. E. Koditschek, "RHex: a simple and highly mobile hexapod robot," *Int. Jour. of Robotics Research*, vol. 20, no. 7, 2001, pp. 616-631.

[7] J. G. Cham, S. A. Bailey, J. E. Clark, R. J. Full, and M. R. Cutkosky, "Fast and robust: hexapedal robots via shape deposition manufacturing," *Int. Jour. of Robotics Research*, vol. 21, no. 10-11, 2002, pp. 869-882.

[8] R. B. Mcghee and A. A. Frank, "On the stability properties of quadruped creeping gaits," *Mathematical Biosciences*, vol. 3, no. 1-2. 1968, pp. 331-351.

[9] D. A. Messuri and C. A. Klein, "Automatic body regulation for maintaining stability of a legged vehicle during rough-terrain locomotion," *IEEE Jour. on Robotics and Automation*, vol. RA-1, no. 3, pp. 132-141, 1985.

[10] E. Garcia and P. Gonzalez de Santos, "An improved energy stability margin for walking machines subject to dynamic effects," *Robotica*, vol. 23, no. 1, pp. 13-20, 2005.

[11] M. Fujita and H. Kitano, "Development of an autonomous quadruped robot for robot entertainment," *Autonomous Robots*, vol. 5, 1998, pp. 7-18.

[12] G. S. Hornby, S. Takamura, T. Yamamoto, and M. Fujita, "Autonomous evolution of dynamic gaits with two quadruped robots," *IEEE Transactions on Robotics*, vol. 21, no. 3, 2005, pp. 402-410.

[13] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and the BigDog Team, "BigDog, the rough-terrain quadruped robot," *in Proc. of the 17th World Congress The Int. Federation of Automatic Control*, 2008, pp. 10822-10825.

[14] http://www.bostondynamics.com/, Boston Dynamics company, USA.

[15] K. Arikawa and S. Hirose, "Development of quadruped walking robot TITAN-VIII," *in Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 1996, pp. 208-214.

[16] S. Cordes, K. Berns, and I. Leppanen, "Sensor components of the six-legged walking machine LAURON II," *in Proc. of IEEE Int. Conf. on Advanced Robotics*, 1997, pp. 71-76.

[17] P.-C. Lin, H. Komsuoglu, and D. E. Koditschek, "A leg configuration measurement system for full-body pose estimates in hexapod robot," *IEEE Transactions on Robotics*, vol. 21, no. 3, 2005, pp. 411-422.

[18] R. B. Mcghee, *Vehicular legged locomotion*, The JAI Press, New York 1985.

[19] S. M. Song and K. J. Waldron, *Machines that walk: the adaptive suspension vehicle*, The MIT Press, 1989.

[20] B.-H. Kim, "Centroid-based analysis of quadruped-robot walking balance," *in Proc. of Int. Conf. on Advanced Robotics*, FD1: Humanoid and Walking Robots Session, Munich, Germany, June 22-26, 2009.

Byoung-Ho Kim

He received the Ph.D. in the Dept. of Electronics Engineering, Hanyang University. From 1989 to 1993, he was a researcher with the Dept. of Research and Development of LG Innotek, Kumi, Korea. From 1995 to 1999, he joined the Humanoid Development Project with the Intelligent Robotics Research Center of the Korea Institute of Science and Technology (KIST), Seoul, Korea. From 2002 to 2004, he was a JSPS (Japan Society for the Promotion of Science) Post-doc Fellow with the Dept. of Robotics, Ritsumeikan University, Japan. From 2004 to 2005, he was a frontier research scientist with the Bio-Mimetic Control Research Center in the Institute of Physical and Chemical Research (RIKEN), Nagoya, Japan.

Dr. Kim is currently with the Dept. of Mechatronics Engineering, Kyungsung University, Busan, Korea as an assistant professor. His research interests include intelligent legged & wheeled mobile manipulation, bio-mimetic robotic systems and humanoid robots, grasping and manipulation of dextrous robotic hands, soft manipulation, compliant arm control, hand/arm coordination, neural computation, etc. He is a member of IEEE, KROS, ICROS, KIIS, KSPE, and IEEK.

E-mail: kimbh@ks.ac.kr