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Semi-Passive Dynamic Walking Approach for Bipedal Humanoid Robot Based on Dynamic Simulation

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1. Introduction

The research on the principles of legged locomotion is an interdisciplinary endeavor. Such principles are coming together from research in biomechanics, neuroscience, control theory, mechanical design, and artificial intelligence. Such research can help us understand human and animal locomotion in implementing useful legged vehicles. There are three main reasons for exploring the legged locomotion. The first reason is to develop vehicles that can move on uneven and rough terrain. Vehicles with wheels can only move on prepared surfaces such as roads and rails; however, most surfaces are not paved. The second reason is to understand human and animal locomotion mechanics. The study of the mechanisms and principles of control found in nature can help us develop better legged vehicles. The third reason which motivated the study of legged locomotion is the need to build artificial legs for amputees. Although some effective artificial legs have been built to date, more in-depth research is required to fully understand the mechanisms and movements necessary to substitute the actual limbs.

The research in this paper concerns a group of legged robots known as bipedal walking robots. Research on this subject has a long history; however, it is only in the last two decades that successful experimental prototypes have been developed. The vast majority of humanoid and bipedal robots control the joint angle profiles to carry out the locomotion. Active walking robots (robots with actuators) can do the above task with reasonable speed and position accuracy at the cost of high control efforts, low efficiencies, and most of the time unnatural gaits. WABIAN-2R is among the most successful bipedal walking humanoid robots. In spite of the extensive research on humanoid robots, the actions of walking, running, jumping and manipulation are still difficult for robots.

Passive-dynamic walking robots have been developed by researchers to mimic human walking. The main goal of building passive-dynamic walking robots is to study the role of natural dynamics in bipedal walking. Passive-dynamic walkers use gravitational energy to walk down a ramp without any actuators. They are energy efficient but have weak stability in the gait. In addition, the major cause of the energy loss in the current passive-dynamic walking robots is the instantaneous change in the velocity of the mass centre during each leg transition.

Recently, to overcome the limitations and disadvantages of the above walking robots (active and passive), researchers have proposed energy-efficient walking robots which can be divided into two major research areas. The first research area is the walking robots with actuators which track the optimized joints angle trajectories. The trajectories are determined from an optimization procedure used to minimize an objective function. The second research area is the passive–dynamic robots with direct drive or elastic actuators installed at some of the joints of the biped. Three successful dynamic walking robots are the Cornell Robot, Denise and Toddler. The main goal of developing dynamic walking robots is to increase the efficiency of locomotion.

The bipedal humanoid robot WABIAN-2R was developed in Takanishi Laboratory at Waseda University to simulate human motion. Compared to most bipedal humanoid robots, WABIAN-2R is able to perform a human-like walking with stretched knees during the stance phase while other robots walk with bent knees (Fig. 1). However, its walking performance requires a large torque and a rapid change in velocity. This requires a harmonic drive gear with high ratio to increase the torque as well as a fast rotating motor (Fig. 2). Therefore, WABIAN-2R needs a lot of energy in each walking step with heavy foot and respectively oversized actuators. This is a problem that can be seen in most of the advanced humanoid robots developed for various tasks. However, the energy loss could be prevented by modifying the design of the ankle joint. A spring mechanism could be added at the ankle joint in order to store part of the energy of the robot during the collision phase and to release it by continuing the motion passively. By combining the passive motion and the actively controlled joints, the humanoid robot can realize walking with more similarity to human motion. This paper investigates the idea through simulation of WABIAN-2R with passive ankle joints that has a back actuator attached in series with springs. This study is currently focusing on dynamic motion on the sagittal plane while the lateral plane is fully active.

2. Dynamic simulation

Dynamic simulation could be used the purpose of testing and checking the dynamic motion of a mechanical structured model. It has the advantages of saving cost and risk which are highly needed in a development of a mechanical structure. There are many simulation software have been developed for robotics application, mainly for the industrial robot applications. However, there are some software packages used for mobile robot simulation. For examples, RoboWorks, SD/FAST, OpenHRP, Webots, and Yobotics are used for mobile and legged robot simulation. Webots is high and advanced simulation software used in Robotics simulation. It is use for prototyping and simulation of mobile robots. It has many advanced functions and techniques. Webots is very easy to use and implement. Therefore, we choose it as simulation software for our research.

2.1 Modeling

In order to develop a dynamic simulation, we need to go through several steps. First is modeling where we set up the simulation environment and initial parameters. We set up a full structure of WABIAN-2, based on the specifications (size, shape, mass distribution, friction, .etc) of components of WABIAN-2 (Fig. 3).

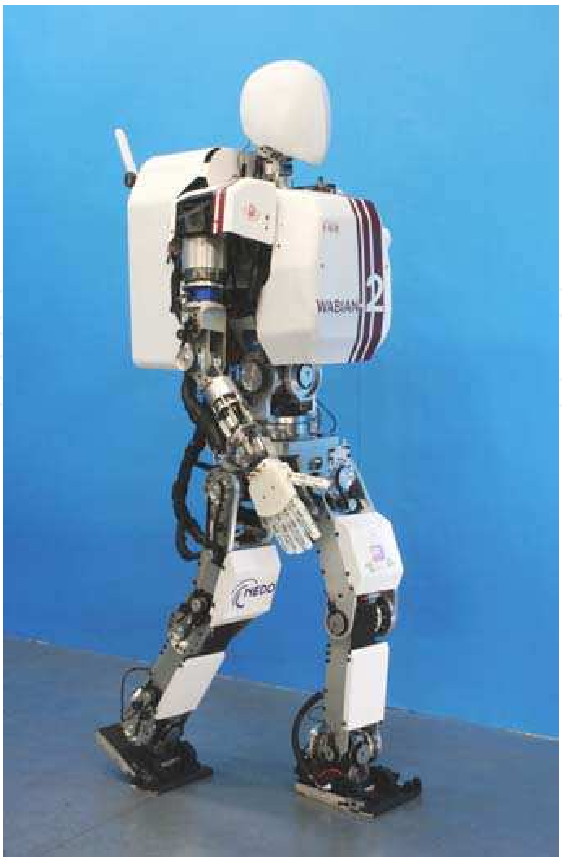


Fig. 1. WABIAN-2R

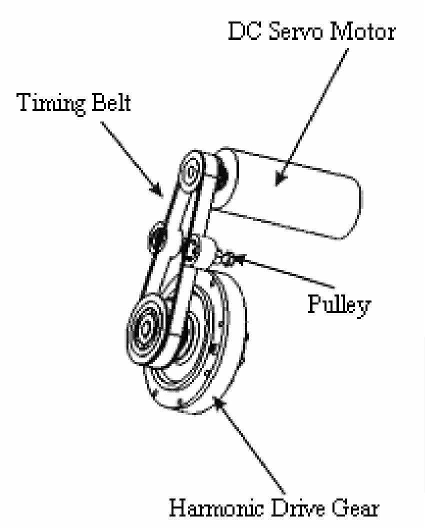


Fig. 2. The Joint Gear System

2.2 Controlling

Second is controlling, which identifies simulation objects and controls the simulation procedures. The controller is some how similar to the WABIAN-2R control. It gets the input data from the CSV pattern file, and sets the position angle of each joint through inverse kinematics techniques. Moreover, the controller sets the simulate time step and the measurement of data.

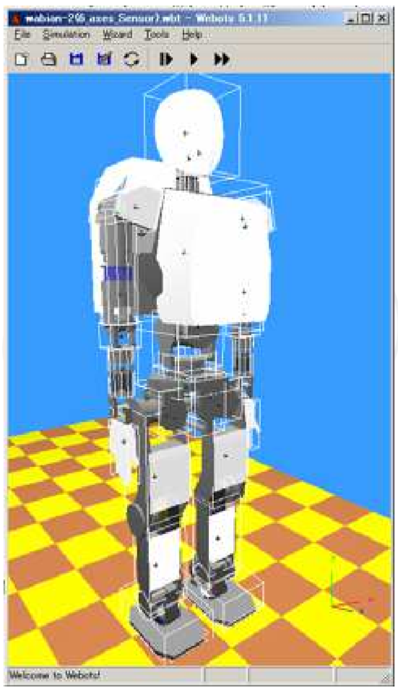


Fig. 3. Modeled WABIAN-2R in the simulation world

2.3 Running

The program in the controller section of the simulator will run by going through the main function. There are several steps the controller will go through. First, check the pattern file and prepare to read through the lines. Then read the data from one line. The data is in terms of position and orientation of foots and hands. Using these data we calculate each joint position through inverse kinematics techniques. After that it will set all positions to its joint. The controller runs one control step of 30ms which is similar to the real robot. The controller goes through all the lines in the pattern file until it is completed in the last line. When the simulation runs it can be viewed the simulation from different view sides. This can gives us a clear idea about the simulation performance. Moreover, most of the needed data could be measured through several functions.

3. Robot model

WABIAN-2R is developed to simulate human motion. Thus the DOF configuration and design structure of the robot is made according to the human body. The design of the robot waist with a 2 DOF helps the robot to perform stretched knee walking, which is similar to the human's. The leg model and ankle joint is detailed in this section.

3.1 Leg model

In most of the passive dynamic walking robots, the legs consist of a hip joint and a knee joint. The knee joint is useful when lifting the leg above the ground during the swing phase. The ankle joint could be eliminated in case that semicircular feet are used. Otherwise, it would be necessary to use an ankle joint in addition to the knee and hip joints.

WABIAN-2R is able to perform a fully stretched walking. This walking is made using only the hip and ankle joints without the use of the knee joint. In this case, the robot leg is simplified from 6 DOF to 5 DOF (3 DOF at the hip and 2 DOF at the ankle). However, the joints movements in the sagittal plane will be made only through 2 DOF (the ankle pitch joint and the hip pitch joint) (Fig. 4).

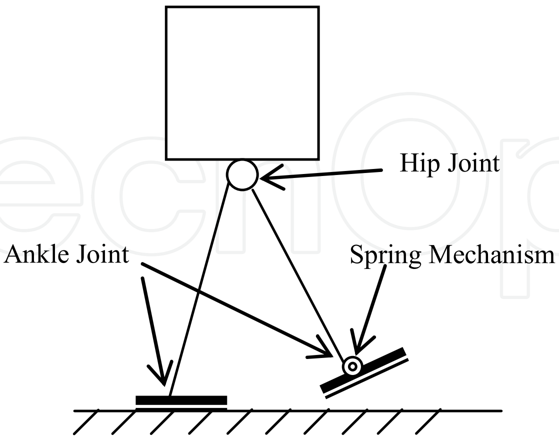


Fig. 4. Simple Robot Model

3.2 Ankle joint

In order to have partly passive walking motion, named by semi-passive motion in this paper, the actuator of the ankle joint in the robot is redesigned in a way to be switched between passive and active mode. Moreover, the ankle should have a level of controllable mechanical compliance for better stability. Therefore, the ankle joint is modified by adding a mechanism called "Rotary Adjustable Stiffness Artificial Tendon" (RASAT). RASAT provides both active and passive rotational motion at the ankle joint. Here we proposed a new design of the ankle, which makes the RASAT bi-directional performing in both active and passive modes. Moreover, it keeps the compliancy of the joint. The elasticity of the joint could overcome the stability difficulties disturbances that might occur in case the foot landing with an orientation (Fig. 5).

The rotary adjustable stiffness artificial tendon (RASAT) is specially designed to provide a wide range of the stiffness (Fig. 6). In RASAT, a pair of compression springs is intentionally inserted between the two concentric input and output links. Each spring pair consists of a low stiffness spring with a stiffness of K1 and a high stiffness spring with a stiffness of K2. The offset between the low and high stiffness springs with value l, is adjustable. Distance d, of the spring pairs with respect to the center of rotation of the links. In this case, the internal torque T, between the concentric input and output links is calculated from:

$$T = \begin{cases} K_1 dx = K_1 d^2 \tan\theta & \dfrac{l}{d} \geq \tan\theta \\ K_1 dl + (K_1 + K_2) d (d \tan\theta - l) & \dfrac{l}{d} < \tan\theta \end{cases} \tag{1}$$

The rotation around the ankle joint is very small, ranging between -0.25 to 0.25. Therefore, the rotation angle equal to:

$$\theta \approx \tan\,\theta \tag{2}$$

From equation (2) the torque provided by the mechanism could be calculated from:

$$T = \begin{cases} K_1 d^2 \theta & \dfrac{l}{d} \geq \theta \\ K_1 d l + (K_1 + K_2) d (d\theta - l) & \dfrac{l}{d} < \theta \end{cases} \tag{3}$$

In addition to RASAT, a back actuator is attached in serial (Fig. 7). The purpose of the Back Actuator is not only to adjust the offset between two springs, but also to provide the required torque at the ankle joint in order for the robot to move forward(Fig. 8).

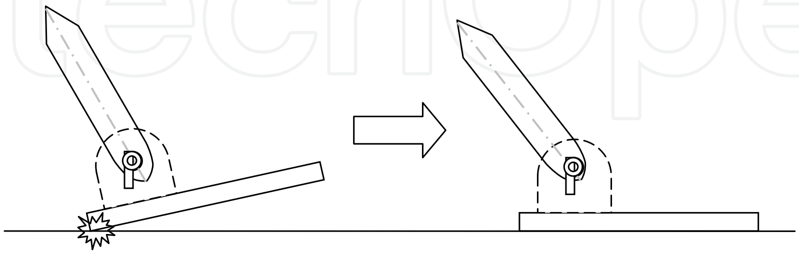


Fig. 5. Foot Landing

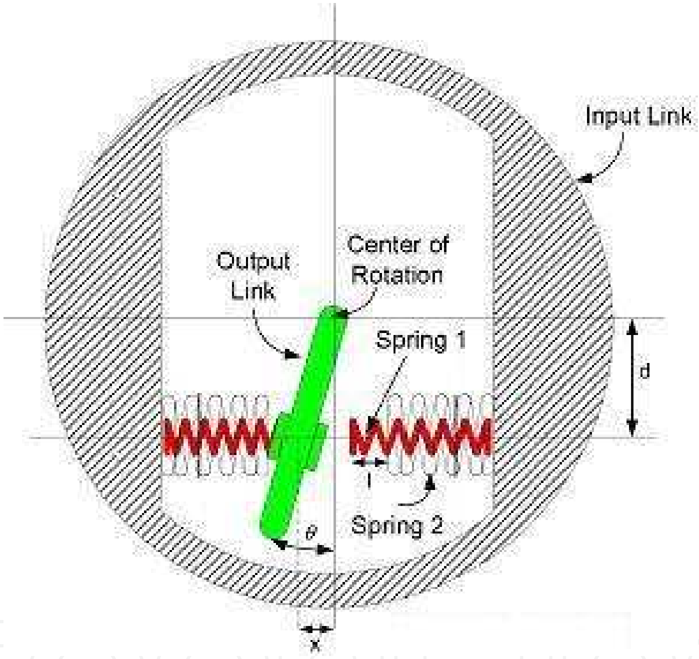


Fig. 6. General schematic of RASAT

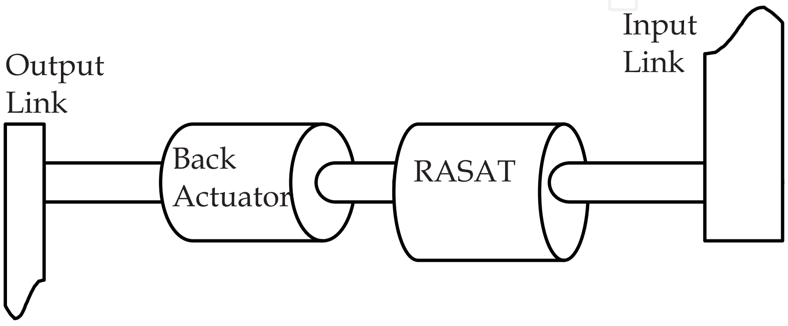


Fig. 7. Structure of Back Actuator connection

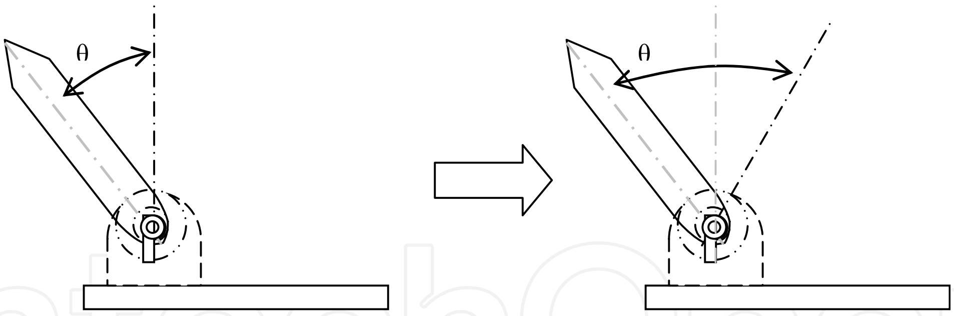


Fig. 8. Changing the Twisting Angle to increase the Joint Torque

4. Walking control

WABIAN-2R is based on joint position control according to the trajectory planning of the foot. The step length and height are calculated from the robot's pattern generator, which provides the robot trajectory planning in joint or Cartesian space.

The stability of passive dynamic walking relies on the energy consumption of the robot. Therefore, the trajectory based joint control method of WABIAN-2R should be partially switched to the torque controlled method instead of position control. Since the ankle joint is set to be passive in this research, the hip joint is the only leg joint that is being controlled. However, in this paper, only the joints on the sagittal plane of the leg are torque controlled while the other joints on the robot are position controlled.

4.1 Hip joint control

The hip joint is controlled using a PD controller to provide the required torque to perform the motion (Fig. 9). The equation for the torque is given below:

$$\tau = K_p(\theta_d - \theta_c) - K_v\omega \tag{4}$$

where K_p is the spring constant gain and K_v is the damper constant gain. θ_d is the reference position set in the pattern, θ_c is the current position, and ω is the joint velocity.

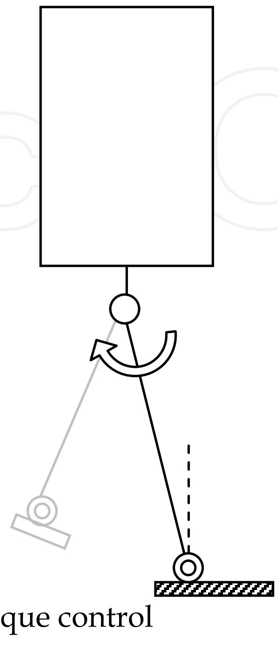


Fig. 9. Hip joint controlled using torque control

4.2 Ankle joint control

The ankle joint provide the required torque in order for the robot to move forward. The design of the joint help to store some the energy in terms of elastic potential energy and release it in form of a joint torque. The control method depends on the mode of action; RASAT mechanism as passive and Back Actuator as active mode.

To have a fully passive mode the offset l in the RASAT is set to maximum value. The makes the low stiffness spring is the only acting spring around the ankle joint. On the other hand, setting the offset to zero will limit the motion making the RASAT unmovable (Fig. 10). In this way the rotation around the ankle pitch joint is only provide the back actuator.

In the case of setting the mode to semi passive, both the RASAT and the back actuator is used. The offset value of l is initially adjusted according to the required torque need. The back actuator controller set the twisting angle according the velocity feedback. The controller the measure the velocity of the robot body and compare it with the reference velocity which set for the robot. The twisting angle increases and decreases according to the amount of differences of the robot velocity. The difference is set in the equation below:

$$\frac{1}{2}m\Delta v^2 = \frac{1}{2}k\Delta\theta^2 \tag{5}$$

From equation (5) the desired spring deflection can be obtained using

$$\Delta\theta = \sqrt{\frac{m}{k}} \cdot (v_d - v_c) \tag{6}$$

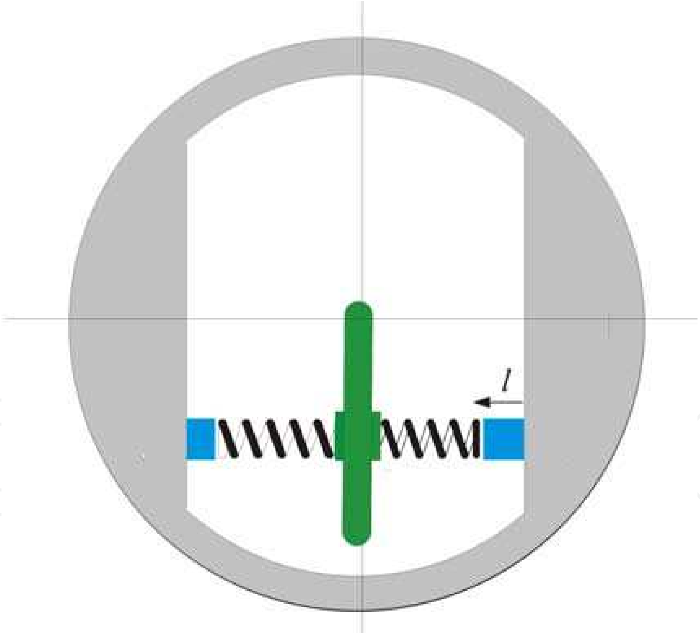


Fig. 10. RASAT mechanism set to active mode

The twisting angle controller is given below:

$$\theta_t(n+1) = \theta_t(n) + G \cdot (v_d - v_c) \tag{7}$$

Where θ_t is the twisting angle, v_d is the desired velocity, v_c is the measured velocity, and G is the control gain. The variable n is the control time step number.

In case that the offset l is set to small value, this can help to provide mechanical compliance. This will support the foot landing in case the foot plane is not in parallel to the surface.

4.3. Robot walking

In order for the robot to make the passive move, it goes through several stages, as shown in Figure 14. First the robot takes the passive leg forward to have a step. Second, the heel of the foot touches the ground (until this stage, there is no energy stored in the passive joint). Third, the joint starts twisting while the leg is forced downward, making the joint store the energy. After the foot landing has been completed, the forward passive motion starts by releasing the stored energy in the passive joint. Finally, the step ends by landing the other foot on the ground. After the step is complete it either stops the motion or takes another step (Fig. 11).

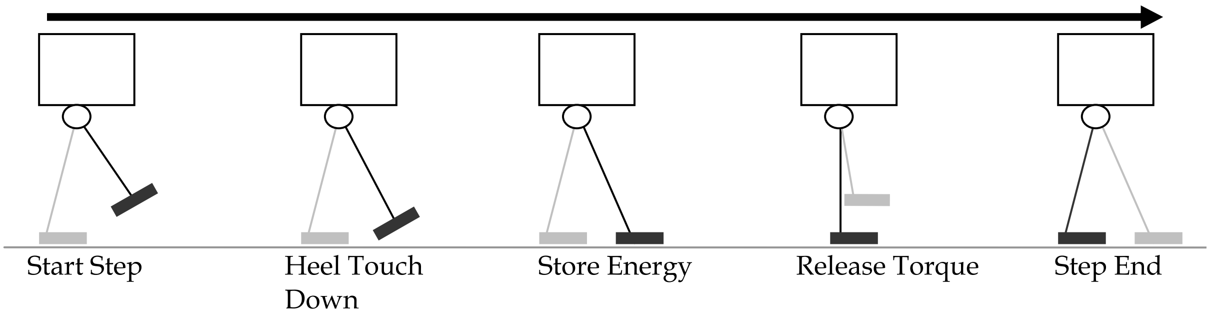


Fig. 11. Passive Step Taking Stages

5. Experiments

Many experiments are conducted in a simulation to check the performance of the robot. WABIAN-2R is simulated with all of its 39 DOF in the simulation package. Different ways were check to achieve the semi passive dynamic walking.

5.1 Natural mode

We conducted many simulations to achieve the semi passive walking using only the spring mechanism on the right ankle pitch. The spring mechanism in the ankle joint is a torsion spring with a stiffness of 50 N.m /rad. The right leg only has the passive joint while the other leg is full active. This helps the robot to stand before it starts to walk. The controller gains for the hip joint are set to Kp = 3000 and Kv = 25.

In the simulation the robot starts by lifting the right leg and pushing it forward using the hip joint. Then the left leg stands on the ground, lifting the whole body of the robot forward using the hip and ankle joints. The right foot, with a passive spring touches the ground and the ankle joint stores energy in the spring during the collision phase. The stored energy provided enough torque to push the body of the robot forward. A semi-passive walking for one step or two steps can be easily achieved (Fig. 12 & Fig. 15). Several other experiments were conducted with different parameters for the controller. Moreover, the spring stiffness was also adjusted and the effects on the walking performance were checked. We realised that the higher the spring stiffness the first steps were difficult for the robot to complete. On the other hand, when the spring stiffness is low, the walking performance goes smoothly but further on the robot velocity becomes slower which makes the robot unable to complete the semi-passive walking.

5.2 Using RASAT mechanism

Many simulations were conducted to achieve the semi-passive walking. Some experiments were successful by setting the ankle joint spring stiffness to 100 N.m/rad which is equal to 160kN/m for the compression spring in the ASAT mechanism. For the hip joint torque control the spring constant (K_p) is set to 5000 and the damper constant (K_v) is set to 25. Both ankle pitch joints are set to active mode in order to keep the robot standing before start walking. Whence the robot gain some velocity for it motion both joint are set to passive mode to be passive dynamic walking motion. A simulation was conducted and the robot was able to walking for 8 steps (Fig. 18).

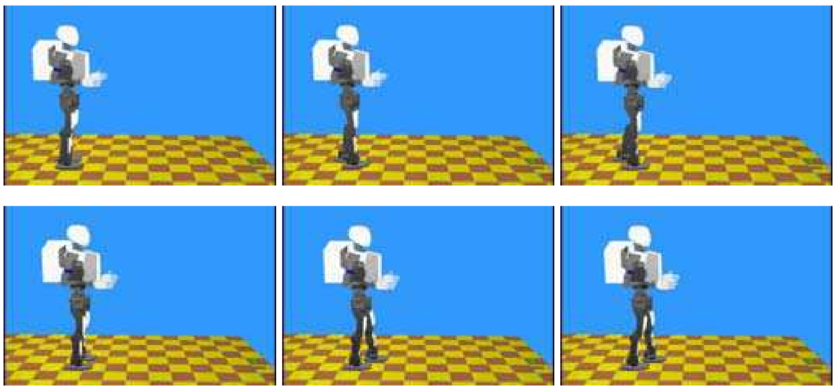


Fig. 12. Simulation of A Semi-Passive Walking for One Step

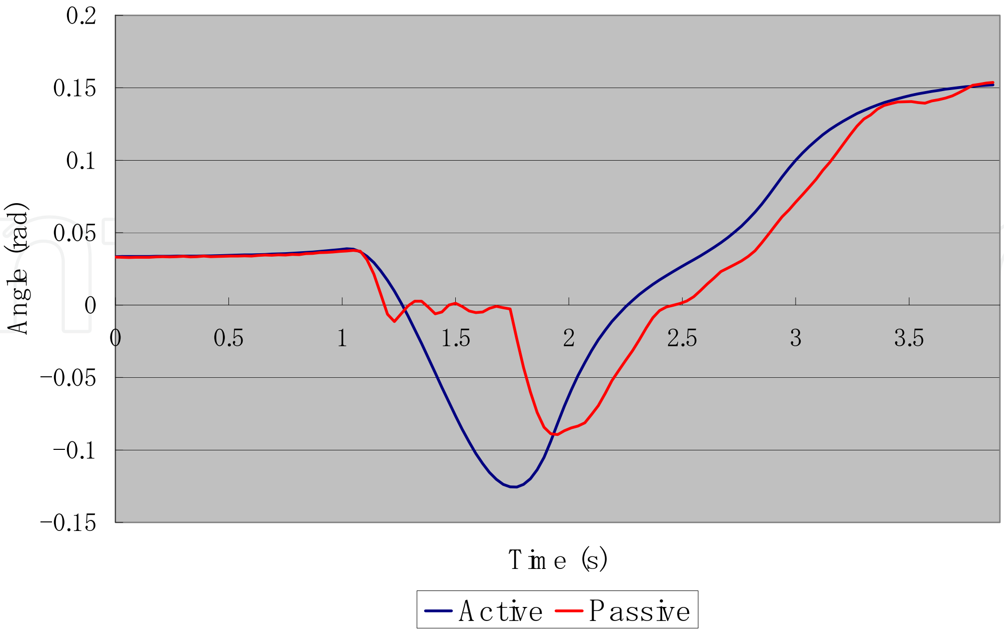


Fig. 13. Passive Joint Angle Measurement

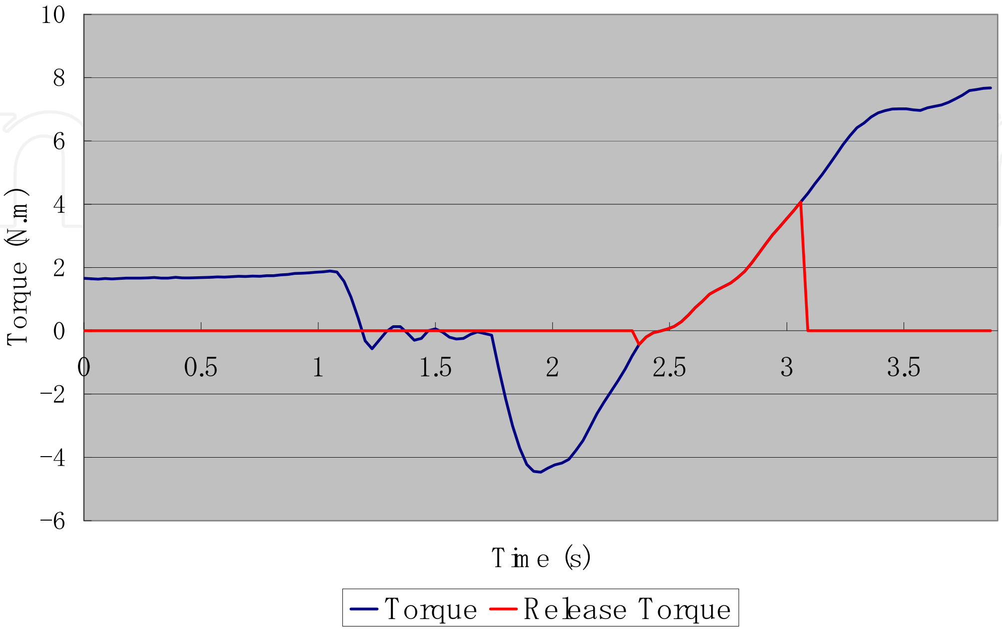


Fig. 14. Passive Joint Torque

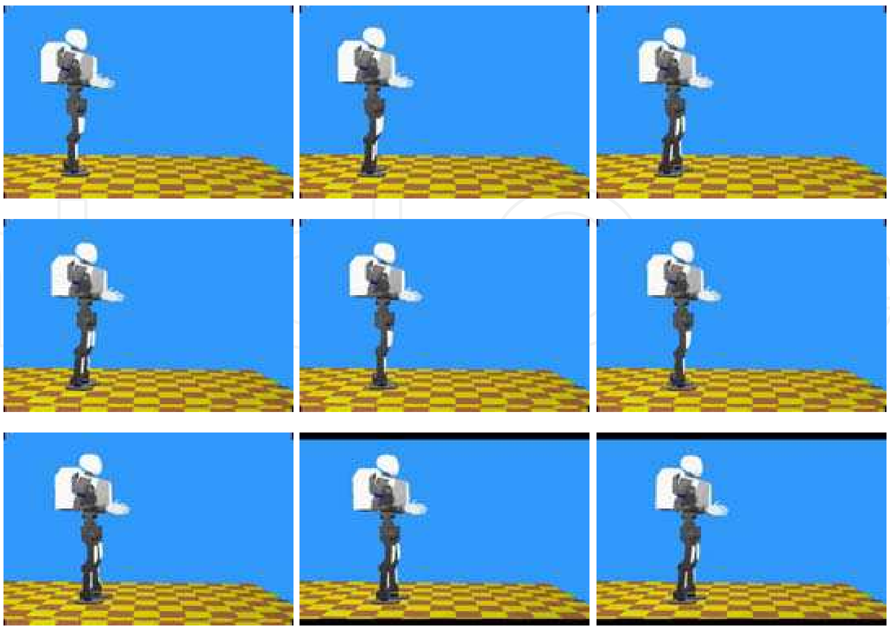


Fig. 15. Simulation of A Semi-Passive Walking for Two Steps

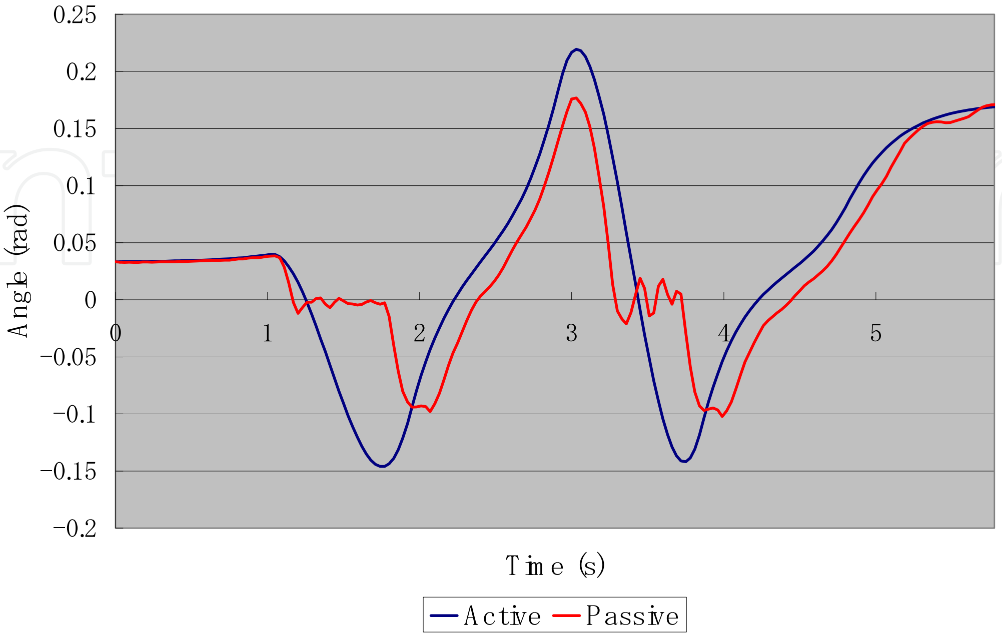


Fig. 16. Passive Joint Angle Measurement

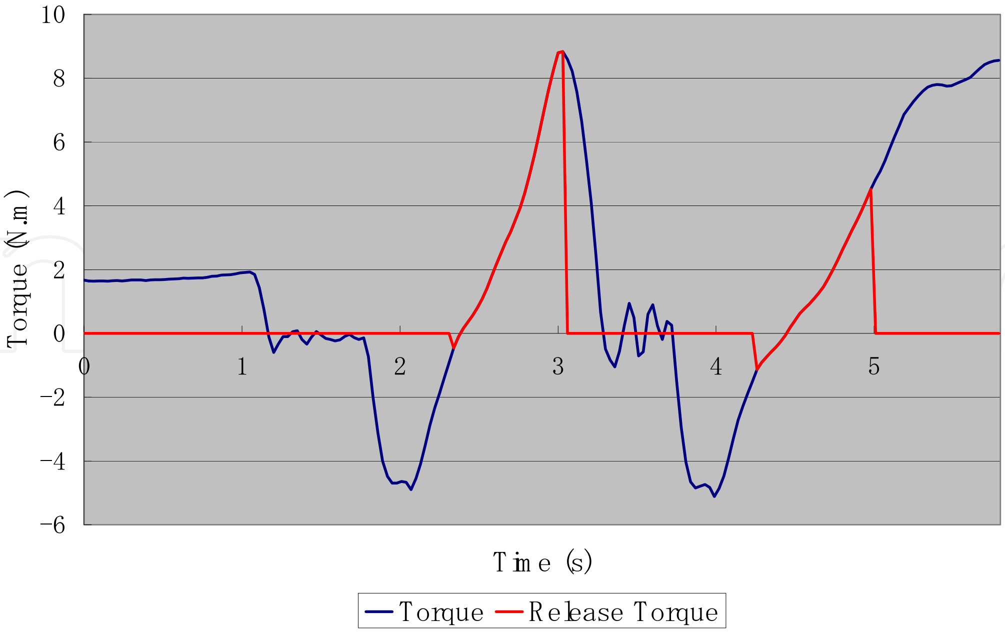


Fig. 17. Passive Joint Torque

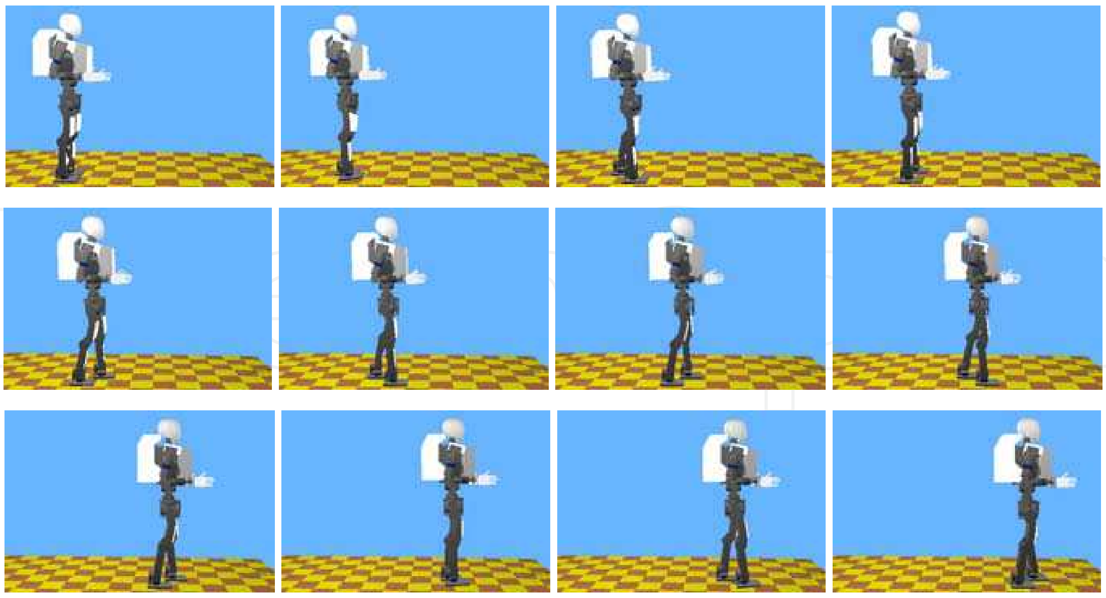


Fig. 18. Simulation for semi passive dynamic walking using RASAT mechanism

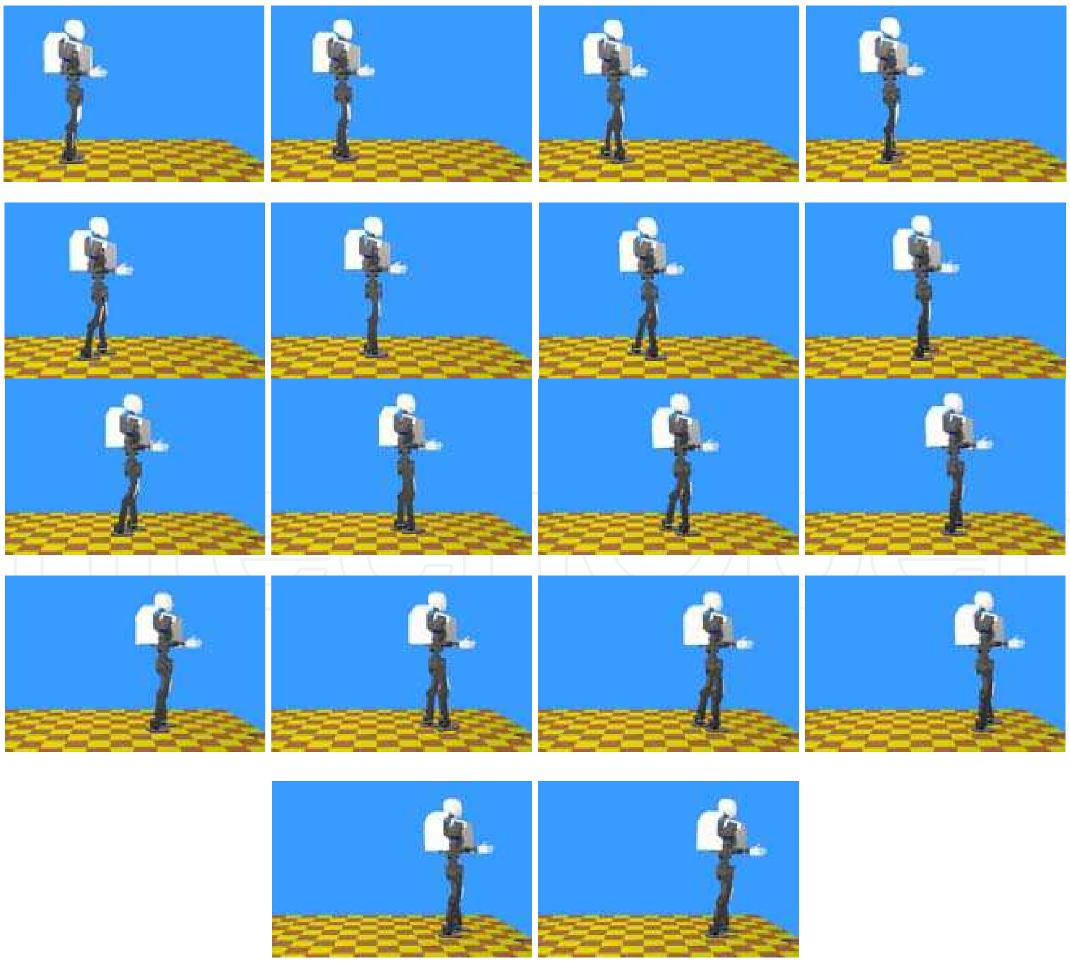


Fig. 19. Simulation for Semi-Passive Walking with a Back Actuator

5.3 With the back actuator

Several simulations were conducted to create a semi-passive walking with as many as steps possible. We achieved a semi-passive walking with four steps by using the back actuator controller only during the stance phase (Fig. 19). The compliancy of the ankle joint also improves the robot's stability when the heel touches the ground first, preventing the necessity of a flat foot contact during the collision. Several control gains of the back actuator were experimented by computer simulations. The best gain, providing a stable semi-passive walking, is 0.05 with a small velocity error compared with the reference velocity of the centre of mass (Fig. 20).

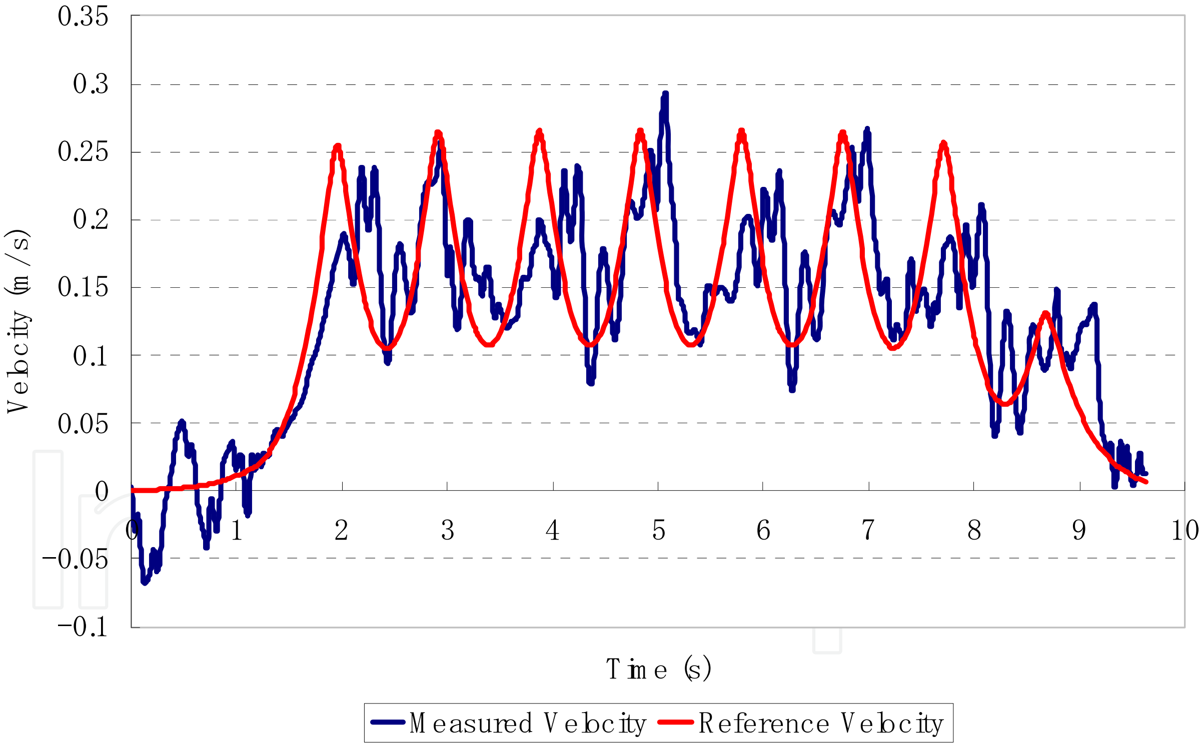


Fig. 20. Robot Velocity Measured Data

6. Conclusions

The semi-passive dynamic walking method is tested in WABIAN-2R using computer simulations. The design of the ankle joint of WABIAN-2R in the computer simulation is modified to include an elastic element in series with the pitch actuator. This allows the robot to perform a semi-passive dynamic walking. The results demonstrate that the semi-passive walking can be realized by using a 100 N.m/rad of torsion spring at the ankle joint for eight walking steps. However actuation and torque control of the ankle joint is necessary for lower stiffness values, 50 N.m/rad. In that case, different control gains are tested to obtain the best value. In addition, using a torque control at the hip joint is required to push the robot forward. Adjusting the stiffness of the ankle joint can be helpful in sustaining the semi-passive motion.

7. References

T. McGeer, “Passive dynamic walking”, The International Journal of Robotics Research 9 (1990) 62–82.

M. Coleman, A. Ruina, An uncontrolled toy that can walk but cannot stand still, Physical Review Letters 80 (16) (1998) 3658–3661.

M.S. Garcia, Stability, scaling, and chaos in passive dynamic gait models, Ph.D. thesis, Theoretical and Applied Mechanics, Cornell University, May 1999.

S.H. Collins, M. Wisse, A. Ruina, A three-dimensional passive-dynamic walking robot with two legs and knees, International Journal of Robotics Research 20 (7) (2001) 607–615.

M. Wisse, J.V. Frankenhuyzen, Design and construction of mike; a 2d autonomous biped based on passive dynamic walking, Adaptive Motion of Animals and Machines (2006) 143–154.

(2005) The TRN homepage. [Online]. Available: http://www.trnmag.com/Stories/2005/022305/Humanoid_robots_walk_naturally_022305.html

M. Wisse, Essentials of dynamic walking: analysis and design of two-legged robots, Ph.D. thesis, Man Machine Systems, T.U. Delft, 2004.

R. Ghorbani, On controllable stiffness bipedal walking, Ph.D. thesis, Mechanical and Manufacturing Engineering, University of Manitoba, Canada, 2008.

Webots. http://www.cyberbotics.com. Commercial Mobile Robot Simulation Software.

Yu Ogura, Hiroyuki Aikawa, Kazushi Shimomura, Hideki Kondo, Akitoshi Morishima, Hun-ok Lim, and Atsuo Takanishi. “Development of a New Humanoid Robot WABIAN-2,” Proceedings of ICRA2006, 2006, paper 76-81.

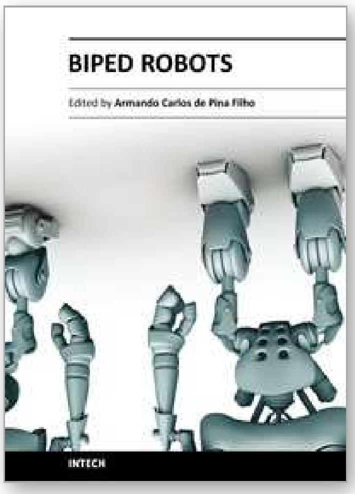
Yu Ogura, Kazushi Shimomura, Hideki Kondo, Akitoshi Morishima, Tatsu Okubo, Shimpei Momoki, Hun-ok Lim, and Atsuo Takanishi. “Human-like Walking with Knee Stretched, Heel-contact and Toe-off Motion by a Humanoid Robot”. Proceedings of the 2006 IEEE/RSJ, IROS2006, 2006, paper 3976-3981.

Yu Ogura, Teruo Kataoka, Hiroyuki Aikawa, Kazushi Shimomura, Hun-ok Lim, and Atsuo Takanishi. “Evaluation of Various Walking Pattern of Biped Humanoid Robot,” Proceedings of ICRA2005, 2005, paper 603-608.

Ghorbani, R. and Wu, Q., Conceptual Design of the Adjustable Stiffness Artificial Tendons for Legged Robotics. Mechanism and Machine Theory, Vol 44, issued 1 pp 140-161, 2009.

Masaki Ogino, Koh Hosoda, and Minoru Asada, Learning Energy-Efficient Walking with Ballistic Walking, Adaptive Motion of Animals and Machines Tokyo, Japan: Springer-Tokyo, 2006, paper 155-164.

Qian Yang, B.G. Shiva Prasad, Peter A. Engel, and Derek Woolatt. “Dynamic Response of Compressor Valve Springs to Impact Loading,” Proceedings of the 1996 International Compressor Engineering Conference, 353-358. West Lafayette, IN, Purdue University.



Biped Robots

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Biped robots represent a very interesting research subject, with several particularities and scope topics, such as: mechanical design, gait simulation, patterns generation, kinematics, dynamics, equilibrium, stability, kinds of control, adaptability, biomechanics, cybernetics, and rehabilitation technologies. We have diverse problems related to these topics, making the study of biped robots a very complex subject, and many times the results of researches are not totally satisfactory. However, with scientific and technological advances, based on theoretical and experimental works, many researchers have collaborated in the evolution of the biped robots design, looking for to develop autonomous systems, as well as to help in rehabilitation technologies of human beings. Thus, this book intends to present some works related to the study of biped robots, developed by researchers worldwide.

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