Gait Planning and Motion Simulation of a Biped Walking Robot

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***Abstract*—A three-step planning method is proposed, aiming at the redundancy of DOFs and the complexity of a biped robot's gait planning. The method presents a quick procedure on the planning of robot's walking gait, and it is used in the walking gait planning of a biped robot, the HIT-Robocean. A robot virtual prototype model firstly is set up with the aid of the softwares, namely, Solidworks, Matlab, and Adams, as a combined simulation, a 3-dimensional animation of its walking gait can be obtained. This virtual prototype model will help to analyse the kinematics and dynamic modes of robot walking gait. Lastly, the walking gait plan is validated in the HIT-Robocean.**

***Keywords*—biped robot; gait planning; virtual prototype; motion simulation.**

I. INTRODUCTION

Gait is the correspondence between each joint of a robot in terms of time and space when the robot walks, which is usually described by means of the movement locus of the joints [1]. Gait planning is used to produce expected gait, i.e. the locus of the joints' movement during a certain period. The realization of this aim relies on an efficient and reliable gait planning method. Gait planning is not only the basis of a robot's stability while walking, but also a key technology in the research of biped walking robots. A practical and effective gait planning method must be developed in order to improve the walking ability of a robot.

It has been proved difficult to harmonize the various joints when a robot walks because of the quantity of joints and complex kinematical chain of a biped robot. The three-step planning method is based on the features of biped robots, the success of which will aid the walking gait planning procedure of robots. Step 1 is to plan the basic posture and locus of the center of gravity on the base of both the movement data of humans and the structural characteristics of biped walking robots. Step 2 is to establish the movement curves of the joints by solving kinematical equations of the biped robot. Step 3 is to amend the movement curves of the joints in order to gain more stable and fluent gaits.

The potential problems can be found in the motion simulation of virtual prototypes before the planned gait is applied in the real physical prototype. This method will give us a simplified devising process, a shortened devising period and a better quality [2]. The final experiment will take place on the physical prototype of HIT-Robocean which is developed by Harbin Institute of Technology, as is shown in Fig.1. The robot is 530mm tall, and weighs 2.05kg. Seventeen mini server motors are utilized as actuators of the joints of the robot. Fig. 2 shows the arrangement of the DOFs of the robot.

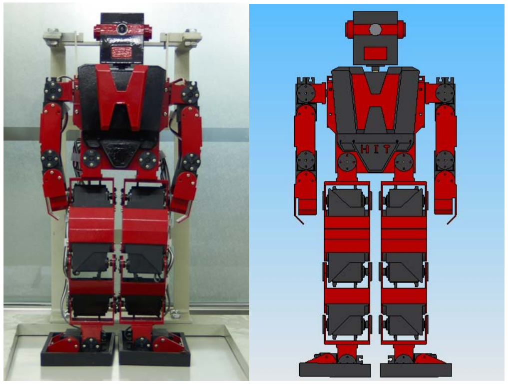

Figure 1. Physical Prototype and Virtual Prototype of HIT-Robocean

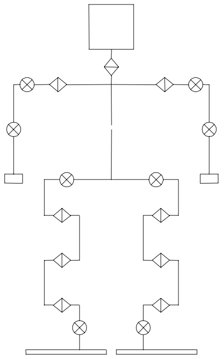

Figure 2. 2 DOF Arrangement of the HIT-Robocean

II. POSTURE AND CENTER OF GRAVITY LOCUS PLANNING

A complete gait planning includes two aspects: posture planning and ZMP (Zero Moment Point) locus planning. Posture is the position of the robot's parts at a specific time when it is walking in the coordinate system. It can be represented by a set of generalized coordinates of the various joints at a certain time [3, 4]. ZMP is the point of intersection on the ground of the extended line which represents the

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combined force of gravity and inertia force. It has been regarded as the most widely-used and believable information in gait planning by now [5, 6]. The formulas are as follows:

$$\begin{cases} \text{Xzmp}=\dfrac{\sum_{i=1}^{n} f_i X_i}{\sum_{i=1}^{n} f_i}=\dfrac{\sum_{i=1}^{n} m_i(\ddot{Z}_i+g_z)X_i-\sum_{i=1}^{n} m_i(\ddot{X}_i+g_z)Z_i}{\sum_{i=1}^{n} m_i(\ddot{Z}_i+g_z)} \\ \text{Yzmp}=\dfrac{\sum_{i=1}^{n} f_i Y_i}{\sum_{i=1}^{n} f_i}=\dfrac{\sum_{i=1}^{n} m_i(\ddot{Z}_i+g_z)Y_i-\sum_{i=1}^{n} m_i(\ddot{Y}_i+g_z)Z_i}{\sum_{i=1}^{n} m_i(\ddot{Z}_i+g_z)} \end{cases}$$

When the robot walks slowly, inertia force can be ignored. In this case, the formulas above can be simplified as the center of gravity projecting equations. The ZMP locus planning is thus simplified as the gravity center locus one:

$$X=\frac{\sum_{i=1}^{n} m_i g X_i}{\sum_{i=1}^{n} m_i g},\quad Y=\frac{\sum_{i=1}^{n} m_i g Y_i}{\sum_{i=1}^{n} m_i g}$$

By researching of HMCD (Human Motion Capture Data) [7-13] and basing the structural features of the robot, the restriction of the basic posture and the movement locus of the robot are presented as below:

- The robot adopts parallel gait, and the locus of each foot remains parallel to the other when it is walking.
- The projection of the robot's gravity center is a sine curve on the ground.
- The hipbone remains at the same height to the ground during walking [14, 15].
- The robot's body keeps vertical to the ground all the time [16, 17].
- The movement orbits of the waving foot are sine curves.
- The soles remain parallel to the ground all the time.

The adoption of sine curves avoids the impact when the robot's center of gravity shifts between the two soles, which also smoothes the shifting angles of the joints. In addition, the movement locus of the waving foot is designed according to sine curves in order to reduce the impact. Therefore, the speed is zero the moment when the foot touches the ground.

III. THE ESTABLISHMENT OF THE KINEMATICS MODEL

The kinematics analysis of biped robot lays the foundation for gait planning. Firstly, the robot kinematics model should be established. Then the kinematics equations are built upon the planned robot's posture and gravity center's movement locus. The solutions to the equations will provide the movement orbits of the robot's joints.

HIT-Robocean adopts the method of off-line planning and on-line adjusting. At the stage of off-line planning, the robot's arms remain still. The planning of the lower limbs joints can enable the robot walk steadily. At the stage of on-line adjusting, the pressure sensor on the soles will calculate the differences between practical position of ZMP and the planned locus [18, 19], which will then be compensated by the waving of upper limbs. The present paper focuses on the off-line stage, so only the movement of the legs is taken into consideration. Fig. 3 shows the joints arrangement of the leg joints.

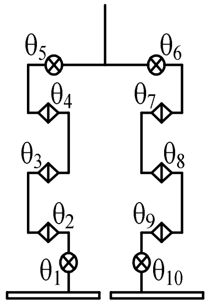

Figure 3. Joints Arrangement of the Leg

The robot's legs have 10 joints in all, which are all rotational joints. Firstly, homogeneous coordinate systems of legs should be established, as is shown in Fig. 4. During the establishment of kinematics equations, the two legs are considered as two serial structures. In solving the kinematics equations, the waving foot movement in connection with that of the supporting foot can be considered as the combination movement of the robot's center to the supporting foot, and the waving foot to the robot's center. Thus a great deal of calculation can be avoided.

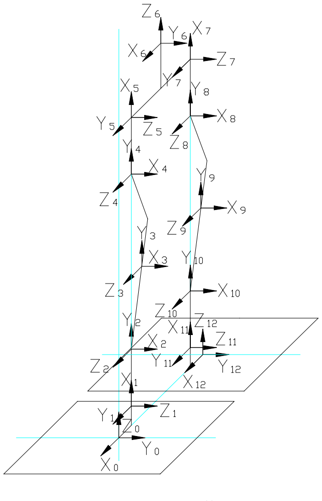

Figure 4. Homogeneous Coordinate Systems of Legs

According to the planned gait, the upper body remains vertical to the ground all the time. The following matrix can thus be obtained:

$${}^{0}T_6={}^{0}T_1\;{}^{1}T_2\;{}^{2}T_3\;{}^{3}T_4\;{}^{4}T_5\;{}^{5}T_6=$$

$$\begin{bmatrix} n_{x1} & o_{x1} & a_{x1} & p_{x1} \\ n_{y1} & o_{y1} & a_{y1} & p_{y1} \\ n_{z1} & o_{z1} & a_{z1} & p_{z1} \\ 0 & 0 & 0 & 1 \end{bmatrix}=\begin{bmatrix} 1 & 0 & 0 & p_{x1} \\ 0 & 1 & 0 & p_{y1} \\ 0 & 0 & 1 & p_{z1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The relationship among the joints angles is obtained:

$$\theta_2+\theta_3+\theta_4=0;\quad \theta_1+\theta_5=0$$

Simplify ${}^0T_6$, and we'll get:

$$P_{x1} = 88S(\theta_1)-45.5-9S(\theta_1)S(\theta_2+\theta_3)+60S(\theta_1)C(\theta_2)+ 79.5S(\theta_1)C(\theta_2+\theta_3)+9S(\theta_1)S(\theta_2)$$

$$P_{y1} = -35S(\theta_5)-9C(\theta_2+\theta_3)-79.5S(\theta_2+\theta_3)+9C(\theta_2)-60S(\theta_2)$$

$$P_{z1} = 50+88C(\theta 1)+79.5C(\theta 1)C(\theta 2+\theta 3)+9C(\theta 1)S(\theta 2)- 9C(\theta_1)S(\theta_3+\theta_2)+60C(\theta_1)C(\theta_2)$$

In the formula, S stands for sin( ), C for cos( ), which will be consistent throughout the paper.

The following matrix can be obtained from the fact that the soles keep parallel when the robot is walking:

$$ {}^6T_{12} = {}^6T_7\, {}^7T_8\, {}^8T_9\, {}^9T_{10}\, {}^{10}T_{11}\, {}^{11}T_{12} =$$

$$\begin{bmatrix} n_{x2} & o_{x2} & a_{x2} & p_{x2} \\ n_{y2} & o_{y2} & a_{y2} & p_{y2} \\ n_{z2} & o_{z2} & a_{z2} & p_{z2} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & p_{x2} \\ 0 & 1 & 0 & p_{y2} \\ 0 & 0 & 1 & p_{z2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The relation among the joints angles is:

$$\theta_7+\theta_8+\theta_9=0;\quad \theta_6+\theta_{10}=0$$

Simplify ${}^6T_{12}$, and we'll get:

$$P_{x2} = -45.5 + 9S(\theta_6)S(\theta_7) - 9S(\theta_6)S(\theta_8+\theta_7) - 88S(\theta_6) - 60S(\theta_6)C(\theta_8+\theta_7) - 79.5S(\theta_6)C(\theta_7)$$

$$P_{y2} = -27/2C(\theta_{10}) - 9C(\theta_7+\theta_8) + 60S(\theta_7+\theta_8) + 9C(\theta_7) + 159/2S(\theta_7)$$

$$P_{z2} = -50 - 79.5C(\theta_6)C(\theta_7) - 60C(\theta_6)C(\theta_8+\theta_7) - 88C(\theta_6) - 9C(\theta_6)S(\theta_8+\theta_7) + 9C(\theta_6)S(\theta_7)$$

IV. THE SOLUTION OF THE JOINTS LOCUS

The forward movement and the sideward movement will be solved separately. When the robot is walking, joints θ_1, θ_5, θ_6 and θ_{10} will rotate to make the robot's center of gravity wave in sine regularity from right to left or vice versa between two supporting feet, which is shown in Fig. 5. From planned gait we know:

$$|\theta_1| = |\theta_5| = |\theta_6| = |\theta_{10}| = \theta$$

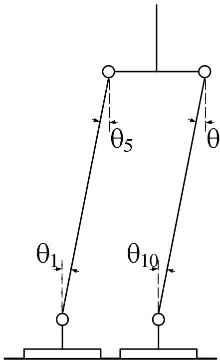

Figure 5. Sideward Movement Joint

After solving out the kinematics equations on the base of the planned gravity center locus, a complete gait (θ) can be obtained, which includes a starting gait period, a normal gait period and a halting gait period [20]. See Fig. 6:

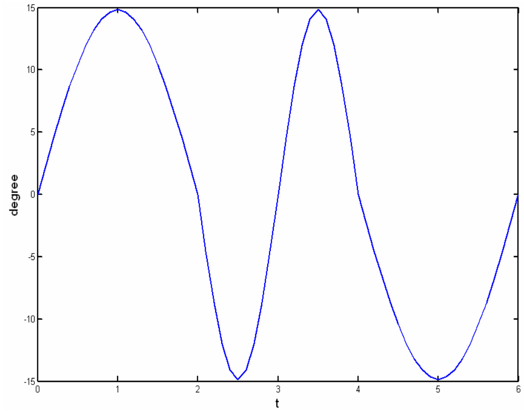

Figure 6. Curves of Sideward Movement

When the robot walks, its two legs step forward alternatively. Forward movement can be realized by joints θ_2, θ_3, θ_4, θ_7, θ_8 and θ_9 . See Fig. 7.

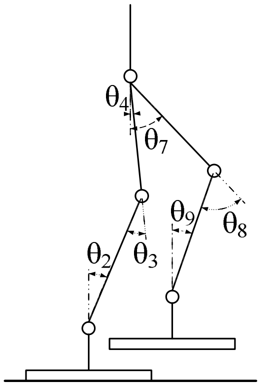

Figure 7. Forward Movement Joint

Assuming that the side joints do not move, that is $\theta_1 = \theta_{10} = \theta_5 = \theta_6 = 0$, we can get the movement curves of the forward joints in connection with time (t) under one gait when we work out the kinematics equations. See Fig. 8. Lastly, superimposed the forward movement on the sideward movement, then we get the walking gait of the robot.

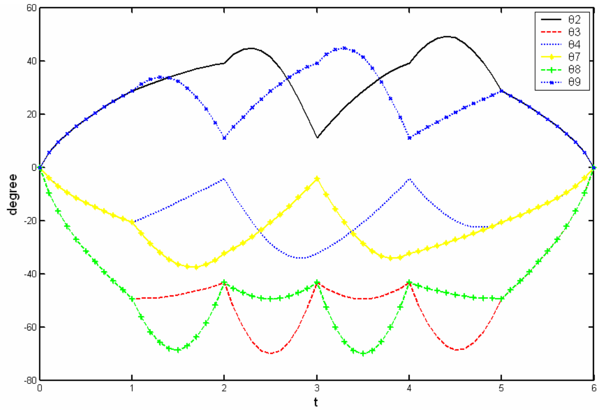

Figure 8. Curves of Forward Movement

V. AMENDING THE LOCUS

When the robot's forward joints and sideward joints move simultaneously, it will fail to keep balance when the gravity center moves into the area between the two soles, which is supposed to be a instable region. The solution to this problem is to enable the robot to stand on both feet during this period. See Fig. 9.

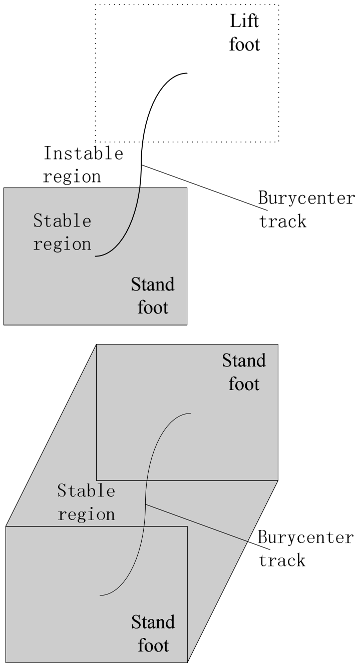

Figure 9. Stable Support Region

The most simple and effective solution is: when the center of gravity is about to move to the central area between both soles (instable region), let the sideward joints stop moving until the robot's feet both play stand feet, and then, the forward joints will stop moving for equal time. At the same time, a stability margin should be set to make sure the center of gravity keep staying within the stable region [21]. This method will efficiently compensate the problem of stable region. The amended movement curves of the joints are as shown in Fig. 10.

Shakes are inevitable when the waving foot touches the ground. As the shakes accumulate with time, the robot tends to be walking unstably. Cumulative errors can be minimized if both the forward joints and the side joints stop moving for some time during one gait period, which can be an effective aid.

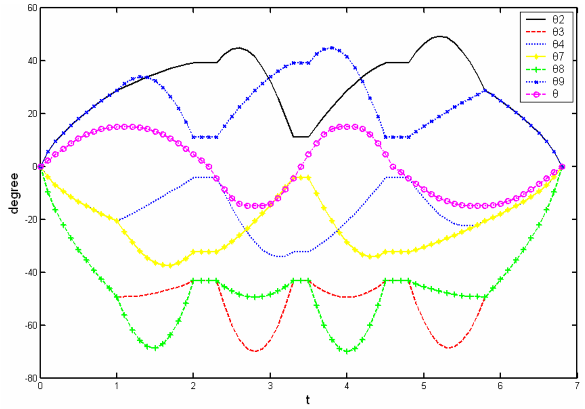

Figure 10. Curves of Forward Movement Joint after Amendment

Refer to Fig.11 for the forward body movement locus; Fig.12 for the sideward movement locus of center of gravity.

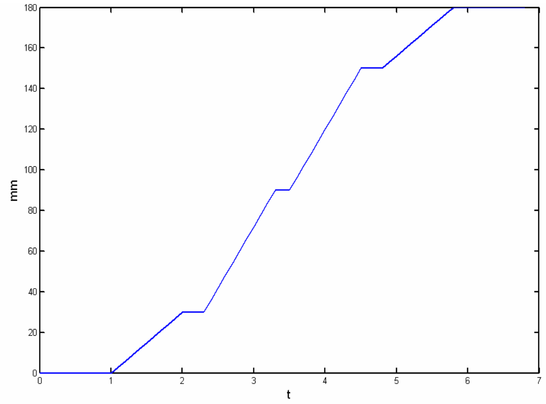

Figure 11. Curves of Forward Movement of Center Gravity

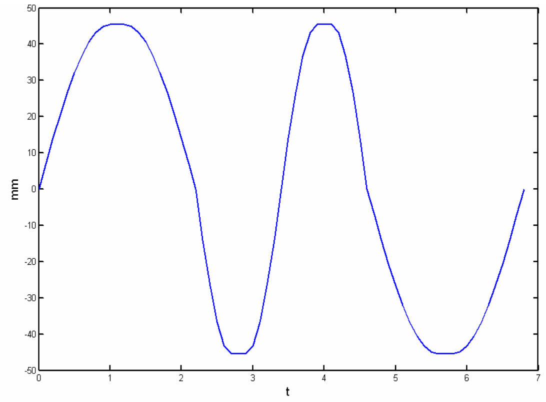

Figure 12. Curves of Sideward Movement of Center Gravity

In order to validate the efficiency of the gait planning, a robot two-pole model has to be made under MATLAB circumstances. According to the movement curves of the joints, sideward movements and forward movements can thus be simulated, as is shown in Fig. 13. The result of simulation indicates that the curves of joints confirm to the planned gait.

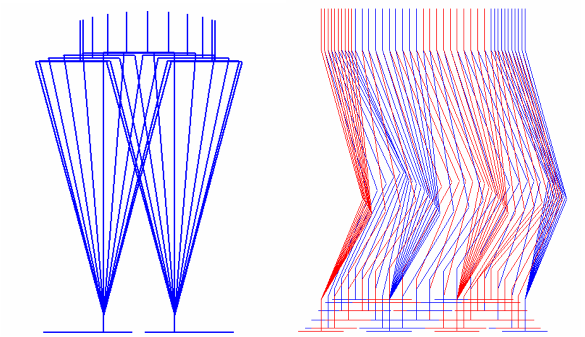

Figure 13. Walking Simulation in Matlab

VI. BUILD THE VIRTUAL PROTOTYPE MODEL

Simulation experiments are implemented on the virtual prototype after planning the walking gait. The virtual prototype model should be simple enough in which there should be as few parts involved in the model as possible, as long as the movement simulation is complete [22]. During the initial simulation analysis, the geometric figures and detailed features of the model does not have to be exactly the same as those of the real robot, so a considerable quantity of time would be saved in establishing the model. The key point in this phase is to obtain an initial result by simulation. As long as the parameters of the model, such as weight, center of weight, and moment of inertia, are in line with the real ones, the simulation results can be assumed as being equal to the prototype.

Fig. 14 shows the simplified model of the robot in SolidWorks®. Import this model into Adams and type in the information of the parts, such as names and material. Then identical physical features with those of the real model can be attained on the simplified model, provided that data like the intensity and the center of weight are defined correctly. Meanwhile, “Joint” and “Motion” should be added to the model according to the moving method of the structural components. Lastly, add contact force and friction coefficient between the robot’s feet and the supporting surface. See Fig. 15.

Disperse the moving locus of the joints in Matlab. Then generate a Spline according to the Data Elements in Adams, and assign each of them to the corresponding joint motion through Cubic Fitting Method. In this way, the robot’s joints will move in accordance with the planned locus.

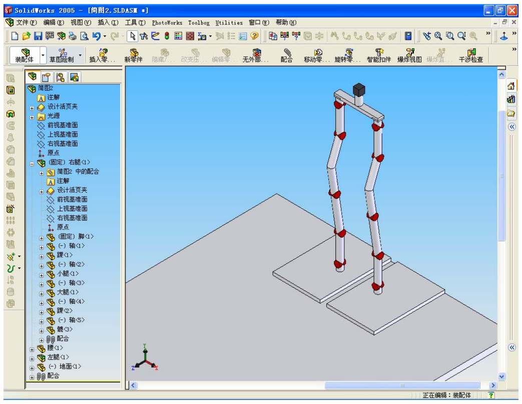

Figure 14. Simplified Model in SolidWorks

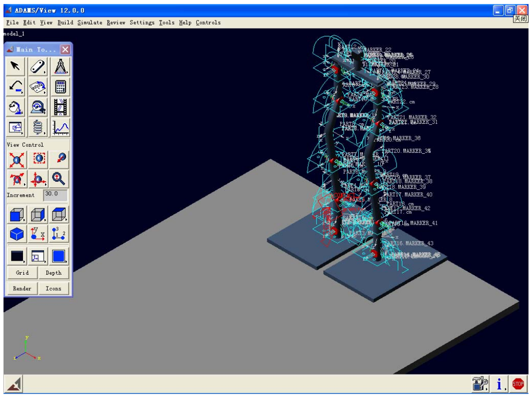

Figure 15. Virtual Prototype Model in Adams

VII. VIRTUAL PROTOTYPE SIMULATION EXPERIMENT

After establishing the model, the Adams/Solver module can automatically generate a set of dynamic equations of the mechanical system model, providing the mathematic results of statistics, kinematics and dynamics. Adams/Postprocessor can be used to output high-quality animations, various data curves, as well as the processing of integral coefficient, differential coefficient, adding, subtracting and error calculating. The two modules function to enable the kinematics and dynamic simulation analysis of the walking gait. The walking animation of the robot is illustrated in Fig.16 and 17.

Figure 16. Walking gait-Front view

Figure 17. Walking gait-Side view

After the simulation, use the Admas/Postprocessor module to post-process the simulation results, and relevant data curves can be generated. Firstly, measure the forward movement locus of the robot's body center, as is shown in Fig.18. The results approximate to the planned locus in Fig. 11.

Applying the formula of the center of gravity, State Variable can be established and locus of the center of gravity can be calculated. Fig. 19 shows the locus of sideward movement of the centre of gravity. The result is acceptably in line with the expected locus shown in Fig. 12, which proves that it is an effective gait planning method to design the gait locus.

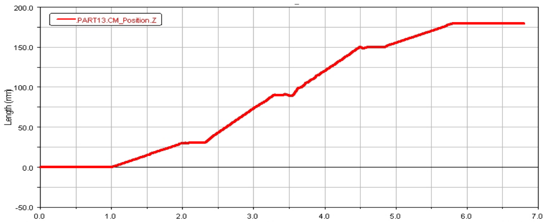

Figure 18. Locus of Forward Movement of the Center of Gravity

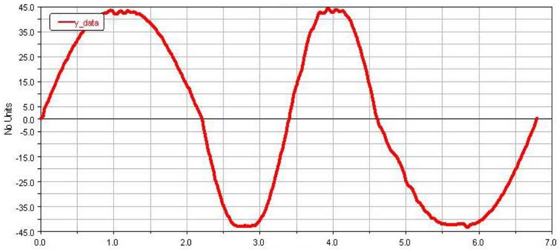

Figure 19. Locus of Sideward Movement of the Center of Gravity

VIII. CONCLUSION

It proves effective to input the planned gait into HIT-Robocean movement-controlling system to motivate the mini server motor. Fig. 18 is the key frames cut from the video of HIT-Robocean while it is walking.

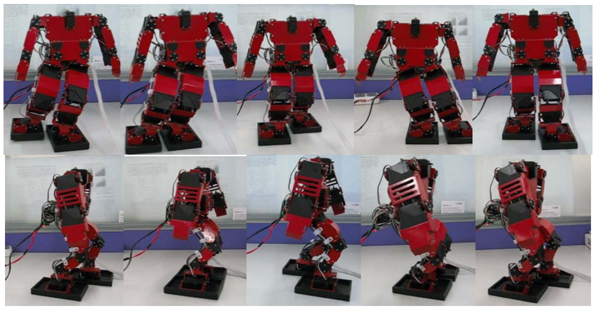

Figure 20. Key Frame of Walking Video

The results prove that the three-step planning method can give satisfactory results in gait planning, providing stable and fluent gait. The method of virtual prototype simulation effectively avoids complex work on dynamic equations derivation. Focus can be put on design, instead of on establishing and solving the equations, which is used to be very tedious. Thus the efficiency is promoted remarkably.

Simulation illustrates a visual walking gait of the biped robot, providing kinematical and dynamic parameters at the same time. This method offers an efficient means of gait planning, and lays a solid foundation for further research on robot kinematics and dynamics.

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