Development of MEL HORSE

Hiroki TAKEUCHI

Ministry of International Trade and Industry
Agency of Industrial Science and Technology
Mechanical Engineering Laboratory Robotics Department, NAMIKI 1-2, 305-8564 Japan
m4890@mel.go.jp

Abstract

Development of Quadruped Robot which has a high mobility performance provides a significant challenge to the robotics engineer. MEL HORSE II is aimed to be such an experimental robot consisting a mechanism for high mobility.

Using the front part of MEL HORSE II, a biped robot could be also developed; it is named MEL Deinonychus II. The characteristic of this robot is that it is equipped with oblong fuselage like as cursorial dinosaurs. In this paper, RHC (Receding Horizon Control) is applied into biped ZMP (Zero Moment Point) control.

1. Introduction

In the case of quadruped robot, Fig.1 shows reptile type and mammal type. Many studies about quadruped robots had been done. Both types have their own advantages. It is depend on the purposed application. If the robot is designed for a construction robot which works on rough terrain, the quadruped reptile type is more advantageous than mammal type. It has the static stability at holding a posture. Reptile type has the advantage in use to move heavy weight at low speed and low consumption. It is like as truck in automobile field.

However, mammal type has the other advantage. It is the fast mobility with long stride and high frequency at any cost. It is like as sports car in automobile field. Studies of this type is few, the study of MEL HORSE is aimed to this type. In this paper, LFD idea, V/H ratio as its measurement of this idea, simulations, high mobility gait are mentioned.

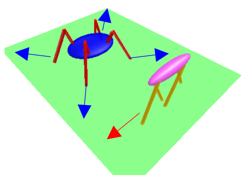

Fig.1 mammal type and reptile type in quadruped

On the other hand, many studies about humanoid (biped) robot are focused recently. One of the problems about these robots is how to control it and how to generate reference leg trajectory. These problems baffle almost designer of legged robots. In this paper, RHC (Receding Horizon Control) is applied onto control biped robot MEL Deinonychus II.

2. MEL HORSE II

2.1 MEL HORSE II

A legged machine named “MEL HORSE” had been developed. MEL HORSE is a quadruped machine and has distinct leg-function between forefeet and hind-feet. The forefeet have the gravity support function and the hind-feet have the generating forward force function. Such distinction of the functions is made by simple counter balance mechanism. Using counter balance, the center of gravity is assigned around front part of the body. Simply it makes the distinct distribution of the leg functions.

Each aluminum pipe frame supports the structure. Aluminum-Duralumin material is adopted at many parts for lightweight. Front part 8.4kg, rear part 6.0kg,fuserage 2.8kg, these are achieved to be lighter weight than MEL HORSE I. Body size 800 * 600 * 250mm. LFD (Leg Functions Distribution) makes main idea of MEL HORSE II mechanism. Linear mechanism using ball screw actuates each rotational joint. Power of the each servomotor is 190W.

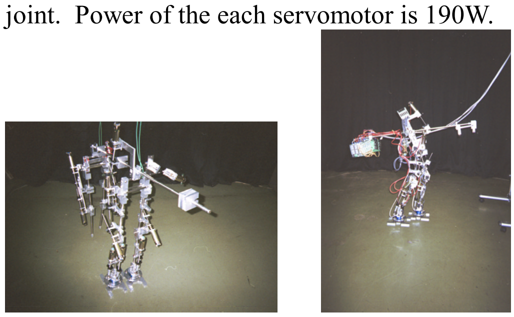

Fig.2.1 MEL HORSE II and MEL Deinonychus II

RT-Linux is adopted for real-time OS. This PC UNIX machine includes interface board “RIF-01”. Encoders at each joint of MEL HORSE II output (2000 pls/r) into up/down counter in RIF-01.

2.2 LFD

The functions required for a leg are discerned gravitational support function and generating forward force function. Previous legged robot has leg combined with these 2 functions, particularly biped robot.

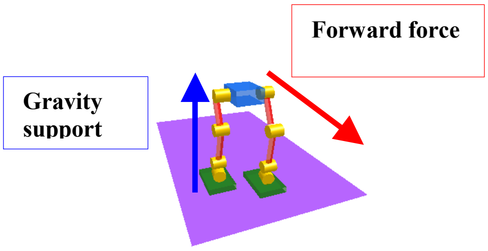

Fig.2.2.1 Leg functions

Quadruped robot has redundancy in number of legs, could be there advanced use of legs for these functions? LFD (Leg Functions Distribution) idea solute this problem. . This idea is simply realized by counter balance mechanism. Fig.2.2.2 shows this idea. The C.G. (centre of gravity) is assigned at front part of the body, and forefeet mainly cover gravitational support function, hind-feet mainly covers generating forward force function.

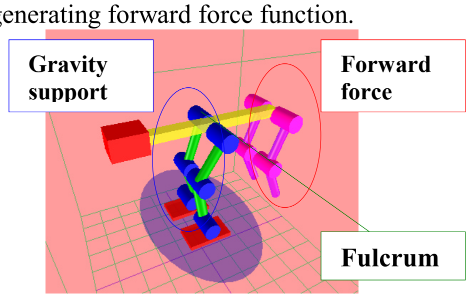

Fig.2.2.2 LFD2.3 Leg posture using DME

In this chapter, numerical analysis using DME (Dynamic Manipulability Ellipsoid) is described. In an analysis of manipulator DME is popular and useful tool, and it is also useful to evaluate LFD. DME is more effective than ME (Manipulability Ellipsoid) because that ME does not include model dynamics. DME is more effective for fast, frequent motion like as leg motion. State space equation of motion is described as;

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) \tag{1}$$

$$\Theta = \begin{bmatrix} \theta_1(t) \\ \vdots \\ \theta_n(t) \end{bmatrix}, \boldsymbol{\tau} = \begin{bmatrix} \tau_1(t) \\ \vdots \\ \tau_n(t) \end{bmatrix}$$

Θ :Joint vecor, τ :joint torque vector, M:Inertial matrix, V:centrifugal force, coriolis force term, G:gravity term

Velocity at the tip of the leg v and joint angle velocity $\dot{\Theta}$ are related as;

$$v = J(\Theta)\dot{\Theta} \tag{2}$$

J is jacobian matrix. Derivate both side,

$$\dot{v} = J(\Theta)\ddot{\Theta} + \dot{J}(\Theta)\dot{\Theta} \tag{3}$$

From equation (1) and (3),

$$\dot{v} - (I - J^{+}J)\dot{J}\dot{\Theta} = JM(\Theta)^{-1}[\tau - V(\Theta,\dot{\Theta}) - G(\Theta) + MJ^{+}\dot{J}\dot{\Theta}] \tag{4}$$

J^{+} is pseudo inverse of J. Here,

$$\tilde{\tau} = \tau - V(\Theta,\dot{\Theta}) - G(\Theta) + M(\Theta)J^{+}\dot{J}\dot{\Theta} \tag{5}$$

$$\dot{\tilde{v}} = \dot{v} - (I - J^{+}J)\dot{J}\dot{\Theta} \tag{6}$$

And equation (4) is;

$$\dot{\tilde{v}} = JM(\Theta)^{-1}\tilde{\tau} \tag{7}$$

DME describes the maximum joint torques $\tau_{i\max}$ as the maximum acceleration $\dot{\tilde{v}}_{j\max}$ at the tip of the leg. $\tilde{\tau},\dot{\tilde{v}}$ are normalized by $\tilde{\tau}_{i\max},\dot{\tilde{v}}_{j\max}$.

$$\hat{\tau} = \left[\frac{\tilde{\tau}_1}{\tilde{\tau}_{1\max}},\cdots,\frac{\tilde{\tau}_n}{\tilde{\tau}_{n\max}}\right]^T \tag{8}$$

$$\dot{\hat{v}} = \left[\frac{\dot{\tilde{v}}_1}{\dot{\tilde{v}}_{1\max}},\cdots,\frac{\dot{\tilde{v}}_m}{\dot{\tilde{v}}_{m\max}}\right]^T \tag{9}$$

and then,

$$\dot{\hat{v}} = \hat{J}\hat{M}(\Theta)^{-1}\hat{\tau} \tag{10}$$

Here,

$$\hat{J} = T_a J \tag{11}$$

$$\hat{M}(\Theta) = T_\tau M(\Theta) \tag{12}$$

$$T_a = diag[\frac{1}{\dot{\tilde{v}}_{1\max}},\frac{1}{\dot{\tilde{v}}_{2\max}},\dots\dots\dots,\frac{1}{\dot{\tilde{v}}_{m\max}}] \tag{13}$$

$$T_\tau = diag[\frac{1}{\tilde{\tau}_{1\max}},\frac{1}{\tilde{\tau}_{2\max}},\dots\dots\dots,\frac{1}{\tilde{\tau}_{m\max}}] \tag{14}$$

$$\tilde{\tau}_{i\max} = \tau_{i\max} - \left|v(\Theta,\dot{\Theta})\right| - \left|G(\Theta)\right| \tag{15}$$

Inertial matrix used in simulation is;

$$M(\Theta) = \begin{bmatrix} l_{1c}^2 m_1 + l_1^2 m_2 + l_{2c}^2 m_2 + 2 l_1 l_{2c} m_2 \mathrm{Cos}(\theta_2) & l_{2c}^2 m_2 + l_1 l_{2c} m_2 \mathrm{Cos}(\theta_2) \\ l_{2c}^2 m_2 + l_1 l_{2c} m_2 \mathrm{Cos}(\theta_2) & l_{2c} m_2 \end{bmatrix} \tag{16}$$

Centrifugal force and Coriolis force term is;

$$V(\Theta,\dot{\Theta}) = \begin{bmatrix} -2 l_1 l_{2c} m_2 \dot{\theta}_1 \dot{\theta}_2 \mathrm{Sin}(\theta_2) - l_1 l_{2c} m_2 \dot{\theta}_2^2 \mathrm{Sin}(\theta_2) \\ l_1 l_{2c} m_2 \dot{\theta}_1 \mathrm{Sin}(\theta_2) \end{bmatrix} \tag{17}$$

Gravitational term is;

$$G(\Theta) = \begin{bmatrix} g l_{1c} m_1 \mathrm{Cos}(\theta_1) + g l_{2c} m_2 \mathrm{Cos}(\theta_1)\mathrm{Cos}(\theta_2) + g l_1 m_2 \mathrm{Cos}(\theta_1)\mathrm{Cos}(\theta_2)^2 - 2 l_1 l_{2c} m_2 \dot{\theta}_1 \dot{\theta}_2 \mathrm{Sin}(\theta_2) - l_1 l_{2c} m_2 \dot{\theta}_2^2 \mathrm{Sin}(\theta_2) - g l_{2c} m_2 \mathrm{Sin}(\theta_1)\mathrm{Sin}(\theta_2) + g l_1 m_2 \mathrm{Cos}(\theta_1)\mathrm{Sin}(\theta_2)^2 \\ l_{2c} m_2 (g\mathrm{Cos}(\theta_1)\mathrm{Cos}(\theta_2) - g\mathrm{Sin}(\theta_1)\mathrm{Sin}(\theta_2)) \end{bmatrix} \tag{18}$$

2.4 V/H ratio

In this chapter, V/H ratio (Vertical/Horizontal Ratio) is proposed as index of LFD. From LFD idea, vertical force is maximized in gravitational support function and horizontal force is maximized in generating forward force function as possible. V/H ratio measures this fact. V/H ratio describes what the part of the major axis of the ellipsoid could contribute into vertical direction or horizontal direction.

V/Hx ratio is the proportion between the length of the major axis and the length projected from the length of the ellipsoid along X axis onto the major axis (Fig.2.4.1).

V/Hz ratio is the proportion between the length of the major axis and the length projected from the length of the ellipsoid along Z axis onto the major axis (Fig.2.4.1).

$$V/H_x = X\cos\alpha \qquad (19)$$

$$V/H_z = Z\sin\alpha \qquad (20)$$

For example, V/H ratio does not indicate good value at Fig.3.3.

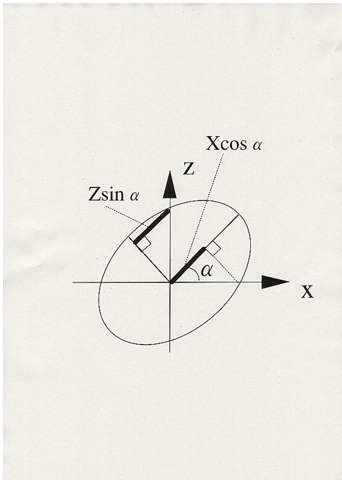

Fig2.4.1 V/H ratio

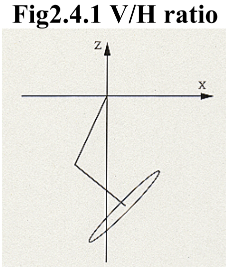

Fig.2.4.2 Negative example

2.5 Numerical Simulation

From Fig2.5.2.1 to Fig2.5.5.2 shows numerical simulation results. Parameters are shown in table2.1. Case1 is $l_1 < l_2$,Case2 is $l_1 > l_2$,Case3 is $l_1 = l_2$.

To define maximum moving velocity, fluid number is adopted. A virtual leg is assumed for whole the robot. The height of C.G. is defined as r;

$$\frac{mv^2}{mgr} \qquad (21)$$

luid number is proportion between gravity acceleration and centrifugal force at its speed. The maximum moving velocity is assigned at fluid number = 1. In the case of $r = 0.5(m)$, vmax=2.23(m/s), if the robot accelerate than this speed, then the body is posed.

Case(1) : Fig2.5.2.1,Fig2.5.2.2 shows the ellipsoids. V means horizontal moving velocity. In this case, v= 2(m/s). Fig2.5.2.2 shows the case that τ_{max} =10(Nm). The direction of the major axis is not uniformed.

Case(2): Fig2.5.3.1,Fig2.5.3.2shows ellipsoids. In the case that the second link is shorter than first link, particularly Fig2.5.3.2, the ellipsoid is slender, and it is no use for both leg functions.

Case(3): Fig2.5.4.1,Fig2.5.4.2,Fig2.5.4.3,Fig2.5.4.4 shows ellipsoids. In the case that τ_{max} =10(Nm), the direction of the major axis is relatively uniformed. Altogether, in the area which x < 0 and z < 0, the ellipsoids are adapted for generate vertical acceleration. In the area which x > 0 and z < 0, the ellipsoids are adapted for generate horizontal acceleration.

When value of τ_{max} is large value, the ellipsoid is slender, then the direction of the ellipsoid is important factor. This means that LFD is important for a robot equipped with large torque actuators.

Fig. 2.5.5.1,Fig. 2.5.5.2 shows V/H ratio about case (3). The postures adapted for vertical acceleration and horizontal acceleration are distinctive. In Fig2.5.5.1, the posture adapted for V/Hx ratio aims generating forward force function. In Fig2.5.5.2, the posture adapted for V/Hz ratio aims gravitational support function.

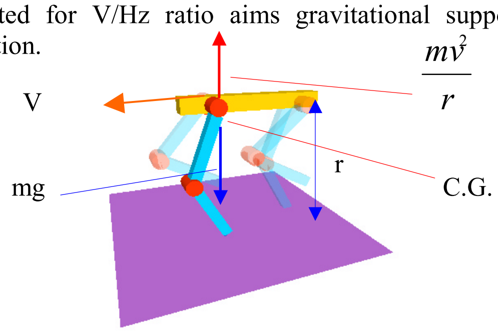

Fig.2.5.1 Definition of Fluid Number

Table 2.1 parameters of 2 link

case1	case2	case3
m_1=1.0 kg	m_1=1.0 kg	m_1=1.0 kg
m_2=1.0 kg	m_2=1.0 kg	m_2=1.0 kg
l_1=0.125 m	l_1=0.375m	l_1=0.25 m
l_{1c}=0.0625 m	l_{1c}=0.1875m	l_{1c}=0.125 m
l_2=0.375 m	l_2=0.125 m	l_2=0.25 m
l_{2c}=0.1875 m	l_{2c}=0.0625m	l_{2c}=0.125m

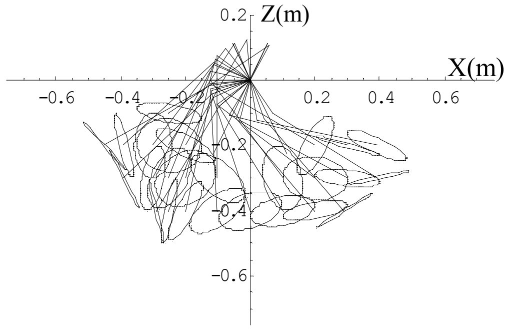

Fig2.5.2.1 Case1 V=2(m/s), $\tau_{\max}$ =1(Nm)

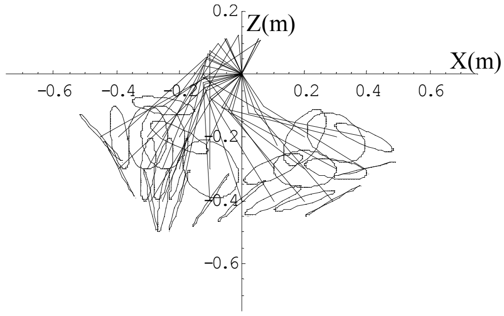

Fig2.5.2.2 Case1 V=2(m/s), $\tau_{\max}$ =10(Nm)

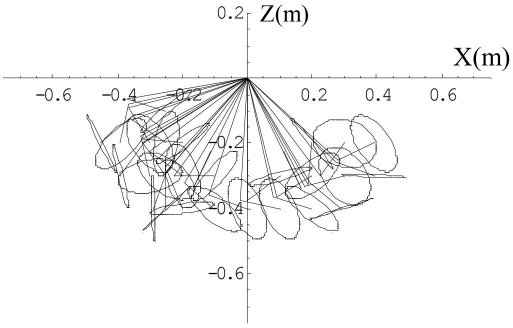

Fig2.5.3.1 Case2,V=2(m/s), $\tau_{\max}$ =1(Nm)

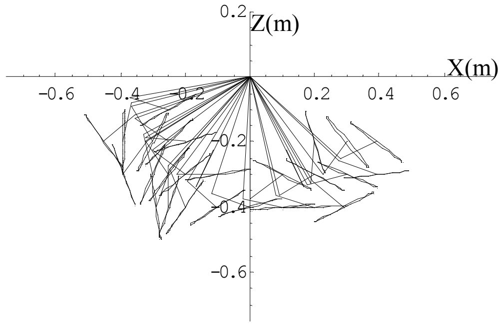

Fig2.5.3.2 Case2 ,V=2(m/s), $\tau_{\max}$ =10(Nm)

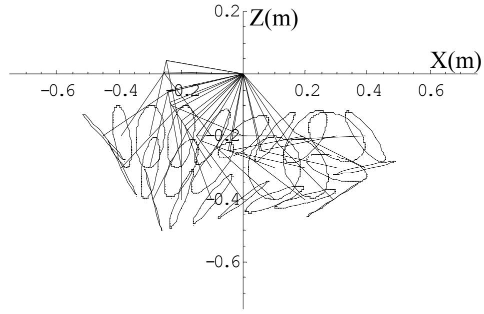

Fig2.5.4.1 Case3,V=2(m/s), $\tau_{\max}$ =1(Nm)

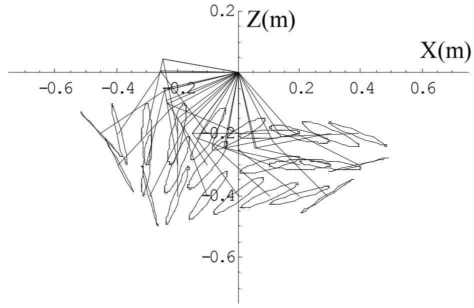

Fig2.5.4.2 Case3,V=2(m/s), $\tau_{\max}$ =10(Nm)

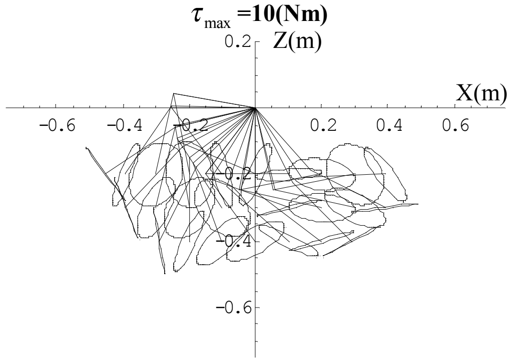

Fig.2.5.4.3 Case3,V=0.5(m/s), $\tau_{\max}$ =10(Nm)

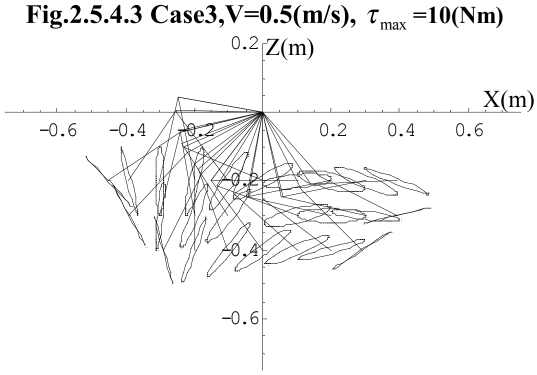

Fig2.5.4.4 Case3 ,V=0.5(m/s), $\tau_{\max}$ =10(Nm)

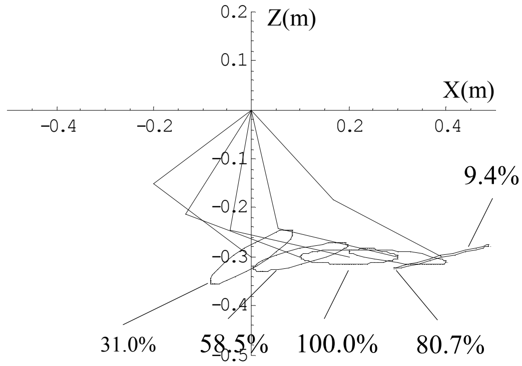

Fig.2.5.5.1 V/Hx Ratio Case3, V=2(m/s), τ_{max} =10(Nm)

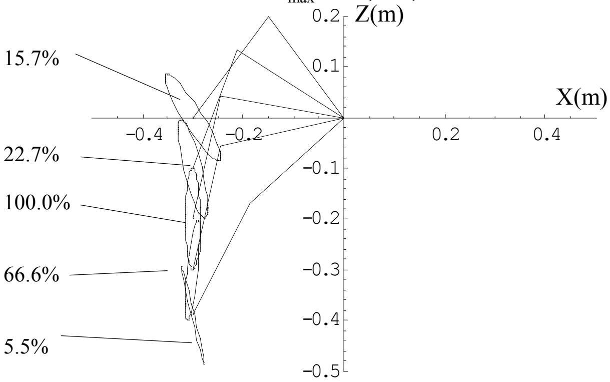

Fig.2.5.5.2 V/Hz Ratio Case3, V=2(m/s), τ_{max} =10(Nm)

3. High Mobility Gait

The gait of quadruped animal change along moving velocity. In this chapter, bound gait which is in high mobility area is considered. In bound gait, it is not effective that the legs merely act the robot upward like as hopping robot. It means that the robot waste the energy for it. In hopping robot, using spring mechanism can avoid this fact.

In this paper, it is proposed to use turnover moment for getting the robot upward in bound gait. Fig3.1 which a horse over a hurdle is helpful to understand this idea.

(Phase I) In Fig.3.2, inertial force $-m\ddot{x}$ rises when hind-feet accelerate the body forward. At this time,

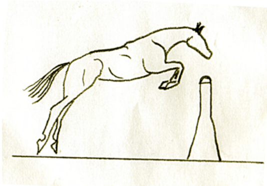

Fig.3.1 Horse jump over a hurdle

the moment around the tip of hind-feet is described as;

$$I\ddot{\theta} = -m\ddot{x}z + mgx \tag{22}$$

If the first term > the second term, the body starts to overturn backward, take off, and the C.G. moves forward.

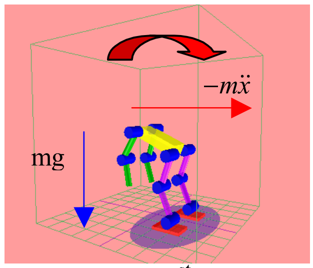

Fig.3.2 1st beat

(Phase II) At the moment of touch down like as Fig.3.3, the overturn moment forward rise because of decelerate force. At this time, if the tip of hind-feet return to front part of the body, then frequent legs motion is available. Ideally, the momentum between these 2 phases is conserved, it is supposed that this motion can be executed without spring mechanism. Off course, the performance of the motion upgrades.

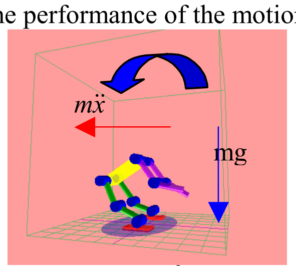

Fig.3.3 2nd beat

4.Receding Horizon Control for Biped

4.1 Receding Horizon Control

In this chapter, let consider how to control ZMP for the biped robot MEL Deinonychus II. The walking sequence is divided into dual support phase and single support phase. At the single support phase in sagittal plane, the robot model behaves like as Fig.4.1. This figure implies TPBVP(Two Point Baundary Value Problem) between initial attitude and final attitude in the single support phase. However, these problem was only available in off-line computing, because gradient method (SCGRA or MQA algorithm) was necessary for solving, then it waste huge calculating time. This is patient of real time control, and fore-running studies divert into a method explicated in the chapter4.2.

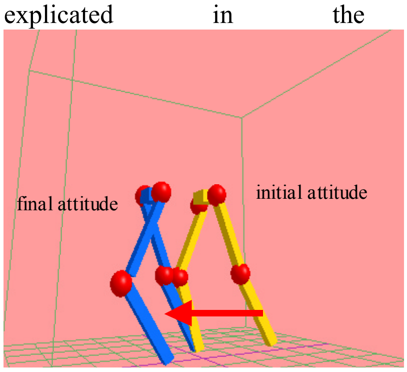

Fig.4.1 TPBVP in single support phase

4.2 Precedent technique of ZMP Control

Generally, the definition of ZMP is described as,

$$x_{zmp} = \frac{\sum_{i=0}^{n} m_i (g+\ddot{z}_i) x - \sum_{i=0}^{n} m_i \ddot{x}_i z_i}{\sum_{i=0}^{n} m_i (g+\ddot{z}_i) x} \qquad (23)$$

For brief, these are represented as,

$$x_{zmp} = \frac{(g+\ddot{z})x - z\ddot{x}}{g+\ddot{z}} \qquad (24)$$

If z is constant value and $\ddot{z} = 0$,then,

$$x_{zmp} = \frac{gx - h_{ref}\ddot{x}}{g} \qquad (25)$$

In the most ordinarily used ZMP control, the height is not able to solve for x axis and z axis simultaneously. It is not able to solve by one on one, then the height of "z" is assumed as a constant. If the reference of ZMP value is larger than real ZMP value, then $\ddot{x}$ is accelerated into forward. If the reference of ZMP value is smaller than real ZMP value, then $\ddot{x}$ is decelerated. Thus it is available to control ZMP by most recently used method. However, this control is not innate, it is dependence of solution on extemporaneous technique.

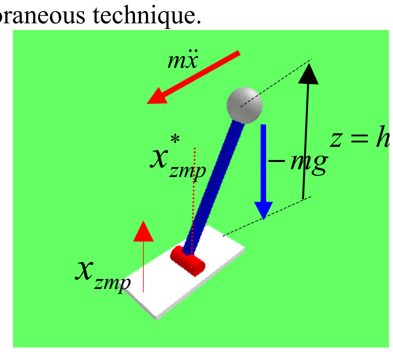

Fig.4.2 Accelerate

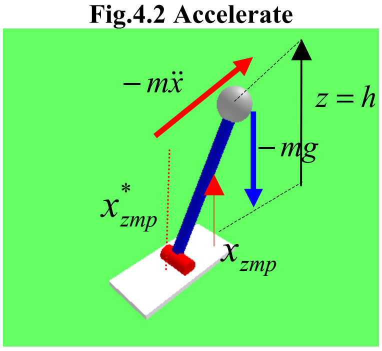

Fig.4.3 Decelerate

In this paper , solution using RHC with equal constraint is proposed, this is essentially solving technique and has real-time performance.

4.3 RHC with equal-constraint

The state equation of the model is described as;

$$\dot{x}^*_\tau(\tau,t) = f_1[x^*(\tau,t), u^*(\tau,t)] \qquad (26)$$

The system has to followed the equal constraint,

$$(-g+\ddot{z})x_{zmpref} - (-g+\ddot{z})x + z\ddot{x} = \mathrm{O} -> f_2[x(t),u(t)] = \mathrm{O} \qquad (27)$$

In this equation, the second and 3rd term are described as ZMP * $(-g+\ddot{z})$ state. And we have the Hamiltonian,

$$H = L + \lambda^* f_1[x^*(t), u^*(t)] + \rho^* f_2[x^*(t), u^*(t)] \qquad (28)$$

Where, we have to consider the performance index moving on τ time axis. "*" means that it is on the τ time axis[12].

$$J = \varphi[x^*(t+T)] + \int_t^{t+T} L d\tau \qquad (29)$$

The solution is derived from TPBVP(Two Point Boundary Value Problem) bellow,

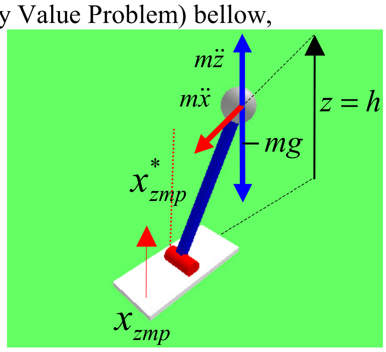

Fig.4.4 ZMP control by RHC

$$\begin{aligned} \dot{x}^*(\tau,t) &= H_\lambda^T ; x^*(0,t) = x(t) \\ \dot{\lambda}^*(\tau,t) &= -H_x^T ; \lambda^*(T,t) = \varphi_x^T[x^*(T,t)] \\ H_u &= 0 \end{aligned} \qquad (30)$$

4.4 Index function for numerical solutions

The model for numerical solutions is defined as ,

$$\frac{d}{dt}\begin{bmatrix} \dot{\theta}_1(t) \\ \dot{\theta}_2(t) \\ \theta_1(t) \\ \theta_2(t) \end{bmatrix} = \begin{bmatrix} M^{-1}(\Theta)\left(\begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} - V(\Theta,\dot{\Theta}) - G(\Theta)\right) \\ \dot{\theta}_1(t) \\ \dot{\theta}_2(t) \end{bmatrix} \qquad (31)$$

This is 2link model in sagittal plane. The performance index of this numerical solution is for the norm of each joint torque.

$$J = \varphi[x^*(t+T)] + \int_t^{t+T} u^*(t)^T u^*(t) d\tau \qquad (32)$$

4.5 Enhanced ZMP for slope terrain

On step or slope, un-even terrain , it is not possible to use ZMP , because ZMP is defined around an ankle on horizontal terrain. At this point , ZMP should be enhanced for un-even terrain. It is assumed an un-even terrain in Fig.4.5. A virtual plane is set like from one foot to the other as the figure. This is same technique of HONDA humanoid robot. If the virtual plane is assigned, it can be to set the origin of the axis on the virtual plane, then ZMP is available to move on the plane to other foot.

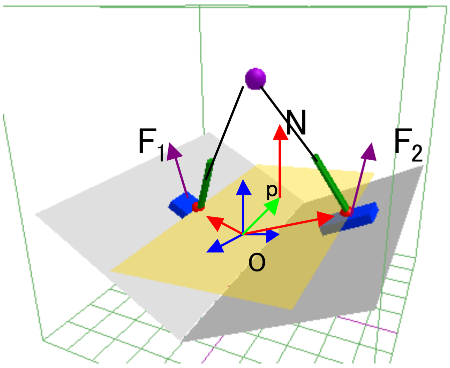

Fig.4.5 virtual plane for enhanced ZMP

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