STEPPING OVER EXCESS OF OBSTACLE FOR BIPED ROBOT BASED ON HYBRID CONTROL

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Abstract: It paid attention to that the stepping over excess of the obstacle by the biped robot can be expressed by HDS (Hybrid Dynamical System) because it was classified into a continuous and discrete event. HDS was made to return to optimal control problem after it had expressed by MLDS (Mixed Logical Dynamical Systems) in consideration of various constraint conditions. In a general ZMP (Zero Momento Point) control, because it is necessary to consider the constraint condition and the optimality separately, it complicates by coexistence of two or more control theories. On the other hand, the stepping over excess of the obstacle with biped robot based on the hybrid control can systematically achieve optimum control because it can treat them in the same way. In this paper, it was shown that the stepping over excess of the obstacle with biped robot was able to return in optimal control problem, and the effect was confirmed by the simulation work.

Keywords: Biped Robot, Stepping Over, Hybrid Control, MLDS

1. INTRODUCTION

Recently, the “Walking” of biped robot is actively researched. There is an advantage that can use a present infrastructure as it is because biped robot can achieve a human walking and the equivalent one. In the research on walking of present biped robot (It was projected on the floor face that the moment of the robot while walking vanished), the method of limiting ZMP (Zero Moment Point) internally in the stability region is mainly used (Vukobaratovich *et al.*, 1990)(Hirai *et al.*, 1998)(Mitobe *et al.*, 2000). Here, ZMP is a point to have projected on the floor face the moment, which depend at gravity and the inertia term of the robot, while walking becoming zero. The walking tracks the foot of biped robot ahead are set beforehand according to the environment of walking, and the posture of biped robot has been decided as ZMP always becomes it while following in the walking track in the stability region.

Next, it pays attention for walking of biped robot. Biped robot operates according to a continuous equation of motion. However, a discrete phenomenon is caused because idling leg and support leg in that case change every time it walks. Moreover, the constraint condition, which the obstacle and the tiptoe of idling leg do not interfere, is necessary before the obstacle is exceeded, and after the obstacle is exceeded, the constraint condition, which the obstacle and the heel of idling leg doesn’t interfere, is needed. That is, the constraint condition is discrete changeable according to the situation, too. When thinking from such a viewpoint, walking of biped robot can be caught as system where continuous event exists together to discrete event.

On the other hand, there is HDS(Hybrid Dynamical System) as system where a continuous event and discrete event exist together (Springer-Verlag, 1993-1998). HDS is known to be can a formulation as the linear inequality, where the logical variable is contained, by the technique named MLDS (Mixed Logical Dyanamical Systems), and can return as optimal control problem (Bemporad and Morari, 1999)(Asano *et al.*, 2002)(Hirana *et al.*, 2002).

In this research, the stepping over excess of the obstacle with biped robot is caught as HDS. Therefore, walking of biped robot is treated as optimal control problem that contains equation of motion and the restraint condition, and the achievement of the stepping over excess of the shortest obstacle is tried.

2. STEPPING OVER THE OBSTACLE BASED ON HYBRID CONTROL

2.1 Stepping Over and Hybrid System

The stepping over excess of the obstacle by two walking can be expressed assuming that a continuous event exists together to the break-up event as shown in Fig. 1. The biped robot steps over the obstacle and the appearance that exceeds it is divided into mode1-mode4 in Fig. 1. The biped robot shows the moving continuously expressed in each mode. On the other hand, the moving of before and after and the support leg and the idling leg of switching expressed discrete is shown between each mode. When the leg (idling leg) expressed in white exceeds the borderline of the obstacle (dotted line), the transition from mode1 to mode2 is done. When the idling leg exceeds the obstacle and it lands on ground, the transition from mode2 to mode3 is done. At this time, the leg expressed in white changes from the idling leg to the support leg, and the leg expressed in the black changes from the support leg to the idling leg. The transition from mode3 to mode4 and the transition from mode4 to mode1 are similarly done with a black leg that is a new idling leg. Thus, the stepping over excess of the obstacle of the biped robot is achieved by the transition of mode1-mode4. However, it is necessary to actually consider the restraint condition concerning the stepping over excess of the obstacle, the center of gravity position of the robot and the operation speed of the robot. These restraint conditions are led in the next paragraph.

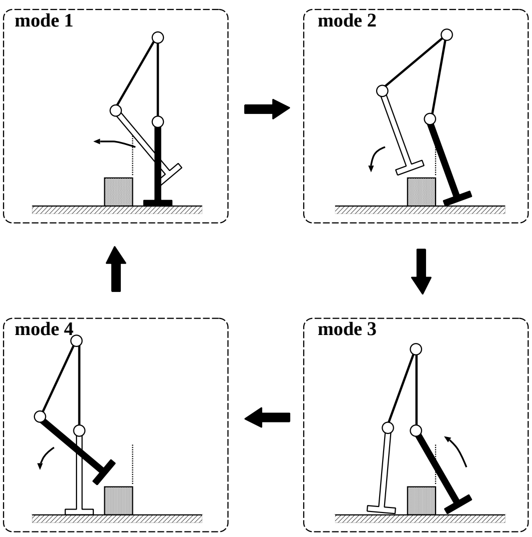

Fig. 1. Automaton of stepping over the obstacle by the biped robot

2.2 Constraint Condition for Realization of the Stepping Over

2.2.1. Constraint Condition of Mode Translation In foregoing paragraph, it explained the mode switch when the biped robot stepped over and exceeded the obstacle. Here, the constraint condition to change the mode is led actually.

The appearance that changes from mode1 from mode2 and mode2 to mode3 is shown in Fig. 2. Tiptoe Q of the robot should exist at the right of upper right of the obstacle$O$ in the state immediately before mode1 changes into mode2 from (a). Moreover, heel P of the robot should exist at the upper part of z_ϵ (> 0) in the state immediately before changing from mode2 into mode3 from (b). These constraint conditions can be expressed as follows.

$$x_q \geq x_o \qquad (1) \qquad\qquad z_p \geq z_\epsilon. \qquad (2)$$

2.2.2. Constraint Condition of Center-of-Gravity The center of gravity position control because of no fall becomes important before the biped robot steps over and exceeds the obstacle. In this paper, it aims at the stepping over excess of the obstacle by the biped robot, and it is not especially related for posture. It is at least assumed that the center of gravity position in which the biped robot doesn't fall is controlled.

The center of gravity position because of no fall of the biped robot is that the center of gravity position always exists the tiptoe of both legs or between. If such a state is shown by the equation as a constraint, it becomes the following expressions.

$$\left[x_q^s \leq x_q^l\right] \;\Rightarrow\; \left[x_q^s \leq G_x \leq x_p^l\right] \qquad (3)$$

$$\left[x_q^s > x_q^l\right] \;\Rightarrow\; \left[x_q^l \leq G_x \leq x_p^s\right] \qquad (4)$$

Here, G_x is a value in which the center of gravity of the biped robot is projected to the X-axis coordinates, x_q^s, x_p^s is a value in which the position with the tiptoe of the idling leg is projected to the X-axis coordinates, and x_q^l, x_p^l is a value in which the position with the

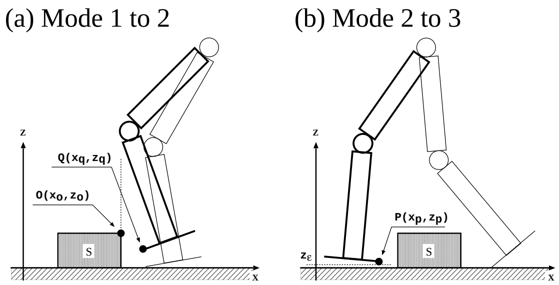

Fig. 2. Condition of mode switching

tiptoe of the saddle support is projected to the X-axis coordinates. Moreover, the idling leg and the saddle support must change depending in the state of mode explained in the foregoing paragraph.

2.2.3. Constraint Condition from Obstable Next, the constraint condition when the biped robot steps over and exceeds the obstacle is led. Figure 3 shows the appearance when the idling leg steps over and exceeds the obstacle. (a) shows the appearance before the obstacle is stepped over and exceeded. It is necessary to carry the tiptoe of the idling leg of the biped robot to the upper part of vestibular ganglion of the obstacle after this while avoiding contact with the obstacle. There is no problem if the height of tiptoe Q of the idling leg is higher than that of ground when Q on the right side from upper right O of the obstacle. However, the idling leg should exist in the over of O if Q is at the left of O. Such a constraint conditions are expressed as follows

$$\left[x_q \geq x_o\right] \Rightarrow \left[z_q \geq 0\right] \tag{5}$$

$$\left[x_q < x_o\right] \Rightarrow \left[g(x_f, z_f, \phi) \geq 0\right] \tag{6}$$

where,

$$g(x_f, z_f, \phi) = \left(x_o - x_f\right)\sin\phi - (z_o - z_f)\cos\phi + \frac{r}{2}.$$

Besides, (b) shows that the idling leg of the biped robot is an appearance before the stepping over excess finishes the obstacle. The idling leg should land forward of the obstacle while avoiding the contact of the heel and the obstacle after this. There is no problem if the height of heel P of the idling leg is higher than that of upperleft R of the obstacle when P is on the right side from R. However, the idling leg should exist over R to make the idling leg land vertically at the left of the obstacle if P is on the left side from R. Such a constraint conditions are expressed as follows

$$\left[x_p \geq x_r\right] \Rightarrow \left[z_p \geq z_r\right] \tag{7}$$

$$\left[x_p < x_r\right] \Rightarrow \left[h(x_f, z_f, \phi) \geq 0\right] \tag{8}$$

where,

$$h(x_f, z_f, \phi) = \left(x_r - x_f\right)\sin\phi - (z_r - z_f)\cos\phi - \frac{r}{2}.$$

(a) Before over (b) After over

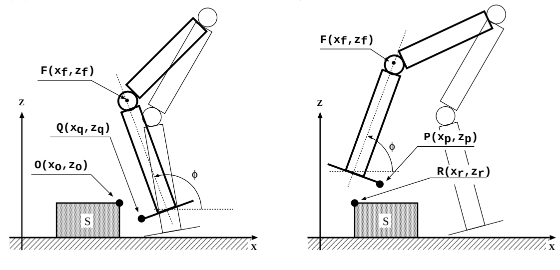

Fig. 3. Constraint based on relationship between obstacle and leg position

2.2.4. Constraint Condition from Moving Velocity The current constraint conditions were a physical constraints that accompanied the stepping over excess of the biped robot. However, the constraint concerning the torque and the velocity exists generally in the motor that drives the biped robot. Then, the equation of motion expressed by the position and the angle is expressed in the following first order models based on the knee joint of the biped robot in Fig. 3.

$$x(k+1) = Ax(k) + Bu(k) \tag{9}$$

$$\begin{cases} x(k) = \left[x_f(k), z_f(k), \phi(k)\right]^T \\ u(k) = \left[u_{xf}(k), u_{zf}(k), u_\phi(k)\right]^T \\ A = \left(1 - \dfrac{\Delta t}{\tau}\right) I_3 \\ B = \left(\dfrac{\Delta t}{\tau}\right) I_3 \end{cases}$$

The constraint concerning the torque and the velocity of the biped robot is expressed by putting the limitation on the input deflection every sampling time intervals. Then, the constraint condition is expressed as follows

$$|u(k) - u(k-1)| \leq \left[M_{xf}, M_{zf}, M_\phi\right]^T. \tag{10}$$

Here, M_{xf}, $M_{zf} and M_\phi$ are the maximum movable amount of knee joint to direction of X-axis, the maximum movable amount of knee joint to direction of Z-axis, the maximum rotatable amount of knee joint leg, respectivery.

2.3 Formulation by MLDS

Up to now, the constraint needed when the biped robot does the stepping over excess of the obstacle has been led. Boolean variable δ to each element of constraint equation (1) and (8) to express the stepping over excess operation of the obstacle by the biped robot with MLDS.

$$\left[x_q \geq x_o\right] \Leftrightarrow [\delta_1 = 1] \tag{11}$$

$$\left[z_p \geq z_\epsilon\right] \Leftrightarrow [\delta_2 = 1] \tag{12}$$

$$\left[x_q^s \leq x_p^l\right] \Leftrightarrow [\delta_3 = 1] \tag{13}$$

$$\left[x_q^l \leq G_x \leq x_p^s\right] \Leftrightarrow [\delta_4 = 1] \tag{14}$$

$$\left[x_q^s \leq G_x \leq x_p^l\right] \Leftrightarrow [\delta_5 = 1] \tag{15}$$

$$\left[x_q \geq x_o\right] \Leftrightarrow [\delta_6 = 1] \tag{16}$$

$$\left[z_q \geq 0\right] \Leftrightarrow [\delta_7 = 1] \tag{17}$$

$$\left[g(x_f, z_f, \phi) \geq 0\right] \Leftrightarrow [\delta_8 = 1] \tag{18}$$

$$\left[x_p \geq x_r\right] \Leftrightarrow [\delta_9 = 1] \tag{19}$$

$$\left[z_p \geq z_r\right] \Leftrightarrow [\delta_{10} = 1] \tag{20}$$

$$\left[h(x_f, z_f, \phi) \geq 0\right] \Leftrightarrow [\delta_{11} = 1] \tag{21}$$

Then, equation (1) and (8) can be expressed as follows.

$$\delta_1 = 1 \qquad (22) \qquad\qquad \delta_2 = 1 \qquad (23)$$

$$[\delta_3 = 1] \Rightarrow [\delta_4 = 1] \qquad (24)$$
$$[\delta_3 = 0] \Rightarrow [\delta_5 = 1] \qquad (25)$$
$$[\delta_6 = 1] \Rightarrow [\delta_7 = 1] \qquad (26)$$
$$[\delta_6 = 0] \Rightarrow [\delta_8 = 1] \qquad (27)$$
$$[\delta_9 = 1] \Rightarrow [\delta_{10} = 1] \qquad (28)$$
$$[\delta_9 = 0] \Rightarrow [\delta_{11} = 1] \qquad (29)$$

Next, such a logical expression is converted into the inequality. First of all, equation (22) and (23) can be converted into the inequality based on equation (11) and (12) as follows

$$\begin{cases} x_q - (M_x - x_o + \epsilon)\delta_1 - x_o + \epsilon \leq 0 \\ -x_q + (x_o - m_x)\delta_1 + m_x \leq 0 \end{cases} \qquad (30)$$

$$\begin{cases} z_p - (M_z - z_\epsilon + \epsilon)\delta_2 - z_\epsilon + \epsilon \leq 0 \\ -z_p + (z_\epsilon - m_z)\delta_2 + m_z \leq 0 \end{cases} \qquad (31)$$

where,

$$\begin{cases} m_x \leq x_q \leq M_x \\ m_z \leq z_p \leq M_z \\ \epsilon > 0 \end{cases},$$

$\epsilon > 0$ is a constant of a positive small enough. In the same way, it converts it into an equivalent inequality for equation (24) to (29) as follows

$$\delta_3 - \delta_4 \leq 0 \qquad (32)$$
$$1 - \delta_3 - \delta_5 \leq 0 \qquad (33)$$
$$\delta_6 - \delta_7 \leq 0 \qquad (34)$$
$$1 - \delta_6 - \delta_8 \leq 0 \qquad (35)$$
$$\delta_9 - \delta_{10} \leq 0 \qquad (36)$$
$$1 - \delta_9 - \delta_{11} \leq 0. \qquad (37)$$

The stepping over excess operation of the biped robot can be as mentioned above described by MLDS.

3. SIMULATION OF STEPPING OVER THE OBSTACLE

It is known to be able to decide the control strategy under the index of a certain kind of optimality by describing the hybrid system as MLDS. The evaluation function was set as follows, and the stepping over excess of the biped robot was simulated. The simulation condition is shown in Table 1. Besides, the simulation result is shown in Fig. 4 to 6.

$$J = \sum_{k=0}^{K-1} \left[\left(\frac{x_f(k) - x^d}{W_x} \right)^2 + \left(\frac{z_f(k) - z^d}{W_z} \right)^2 + \left(\frac{\phi(k) - \phi^d}{W_\phi} \right)^2 \right] \qquad (38)$$

Figure 4 shows the transition of the center of gravity position of the biped robot and the relation to the constraint condition. Figure 5 shows the relation among the position of the idling leg, the position of the obstacle and the relations to the constraint condition. Figure 6 shows the appearance expressed in animation based on the simulation result.

In Fig. 4, the solid line is a center of gravity position, the dotted line is an upper bound at the center of gravity position, and the broken line is a lower bound at one. The constraint requirement expressed by equation (3) and (4) is met from the center of gravity position is always in the bound pair.

Figure 5 (a-1) and (a-2) show the appearance of the constraint condition expressed by (5) and (8) equation when the leg shown in the bold line of Fig. 3 is an idling leg, and (b-1) and (b-2) show the constraint condition expressed by (5) and (8) equation when the leg shown by the thin line of Fig. 3 is an idling leg. Besides, the dash line in figure is a supplementary line to see whether to meet the constraint condition requirement. It is understood that it is $z_q > 0$ according to (a-1) when x_q is at the right of point O the obstacle, which means point O equal 0.67[m] or more. This shows constraint condition (5), and means it meets the requirement. Moreover, it is understood that it is $g(x_f, z_f, \phi) > 0$ when x_q is at the left of point O the obstacle, which means point O is less than 0.67[m]. This shows constraint condition (6), and means it

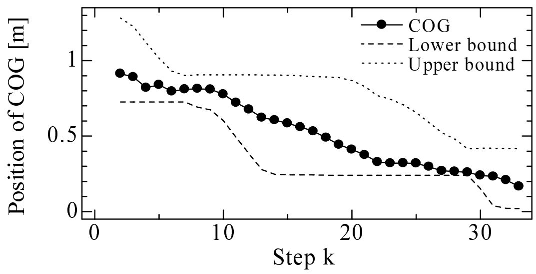

Fig. 4. Results of the stride of biped robot under COG contraints

Table 1. Simulation conditions

Nomenclature	Value	Unit
Simulation step k:	31	
Initial of $Q = (x_q, z_q)$(idling)	(1.126, 0.033)	[m]
Initial of $P = (x_p, z_p)$(idling)	(1.282, 0.093)	[m]
Initial of $F = (x_f, z_f)$(idling)	(0.979, 0.044)	[m]
Initial of $Q = (x_q, z_q)$(support)	(0.726, 0.015)	[m]
Initial of $P = (x_p, z_p)$(support)	(0.906, 0.015)	[m]
Initial of $F = (x_f, z_f)$(support)	(0.816, 0.465)	[m]
Obstacle $O = (x_o, z_o)$	(0.67, 0.19)	[m]
Obstacle $R = (x_r, z_r)$	(0.47, 0.19)	[m]
M_{xf}, M_{zf}, M_ϕ	0.2, 0.2, 2.618	[m],[m],[rad]
W_x, W_z, W_ϕ	1.0, 1.0, 1.0	

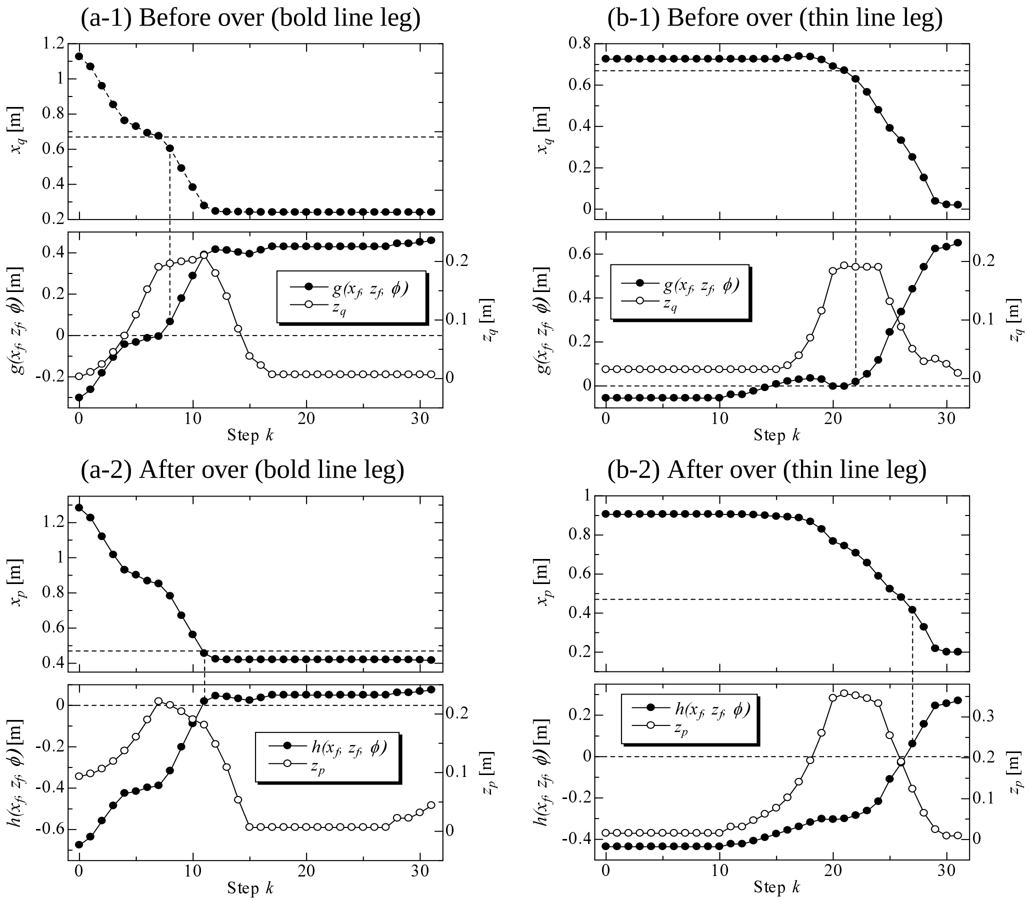

Fig. 5. Results of the stride of biped robot under obstacle contraints

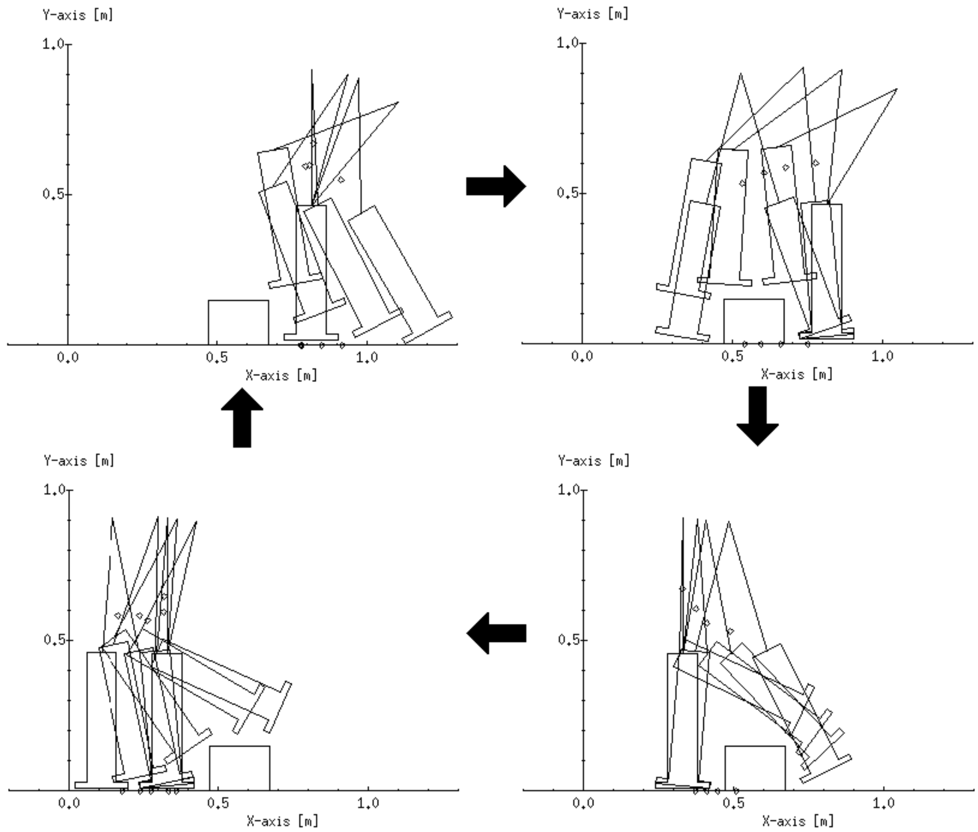

Fig. 6. Result of the stepping over the obstacle by the biped robot

meets the requirement. It is understood that it is $z_p > z_r$ according to (a-2) when x_p is at the left of point R the obstacle, which means point R equal 0.47[m] or more. This shows constraint condition (7), and means it meets the requirement. Moreover, it is understood that it is $h(x_f, z_f, \phi) > 0$ when x_p is at the left of point R the obstacle, which means point R is less than 0.47[m]. This shows constraint condition (8), and means it meets the requirement. The constraint condition (5) and (8) is also filled from (b-1) and (b-2) for the leg expressed by thin line of Fig. 3.

Figure 6 shows the animation which is the stepping over excess of the obstacle by the biped robot. Then it divides into mode1 to mode4 shown in Fig. 1. It can be confirmed that the biped robot steps over and has exceeded the obstacle by the lead of the constraint condition, and the best generation of the control input to the robot that meets the requirement from Fig. 6 visually. The achievement of the stepping over excess of the obstacle by the biped robot was able to be confirmed by simulation work.

4. CONCLUSION

In this paper, it paid attention to a continuous event and the discrete event when the biped robot stepped over and exceeded the obstacle. The constraint condition needed to step over and to exceed the obstacle by the biped robot was derived, and a logical variable was allocated in them to describe the MLDS that expressed coexistence of a continuous event and the discrete event. Moreover, the evaluation function to which the trajectory area of the leg was minimized was set so that the biped robot may step over and exceed the obstacle by the shortest route, and it simulated as the optimal control problem. As a result, it was confirmed to be able to achieve the stepping over excess of the obstacle by the biped robot meeting all the constraint requirements by the simulation.

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