Modeling and Simulation of Quadruped Form Multi-purpose Module System MMS for Stability Control

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Abstract

The Multi-purpose Module System (MMS), which is one of the module robots, consists of joint modules and function modules. It is possible to transform the MMS such as series-connected form and quadruped form and add appropriate sensors. Therefore, the MMS is useful as rescue robot at unknown situation. This paper presents a quadruped form MMS (MMS-G02). Especially, modeling and simulation of the MMS-G02 for stability control is discussed. The inverse kinematics to determine the each leg position is used. And the trajectory of the leg of the MMS-G02 is evaluated by simulation. The results show that the leg is properly moved without collision. An inverted pendulum model for the MMS-G02 is proposed and the MMS-G02 is controlled using a state feedback control to stay in balance. And the effect of friction force between the MMS-G02 and the ground is also evaluated by simulation. The maximum value of the lean of the MMS-G02 is 0.14 rad which is smaller than the maximum angle without contact to the ground. The results indicated that the MMS-G02 can stay in balance and keep on the two legs. In the conclusion, the proposed calculation model is useful in achieving control of the MMS-G02 to adapt a changing environment.

Keywords: MMS, module robot, control, state feedback control, quadruped robot

1 Introduction

There are various situations such as a heap of rubble, collapsed house, submerged vehicle and house, burned-out house in the disaster area. And these situations are scattered over a large area. Currently, we have to prepare the several types of rescue robots to respond to these all situations quickly after disaster, because nearly every robot is especial robot in a particular situation [1-6]. For example, a wheel robot is capable of very fast movement on the smooth load [1, 2]. However, it is difficult to move on an irregular terrain. A crawler robot has mobility on the irregular terrain but not on the high uneven ground [3, 4]. A legged robot is mobility on the irregular terrain, the high uneven ground and stairs [5, 6]. But velocity of the legged robot is slower than the wheel and the crawler robots. And energy consumption of the legged robot is also higher than one of the other robots.

We can only bring the appropriate robot if we know the situation of disaster site. However, it is difficult to know the situation at an early date. Furthermore, it is difficult to prepare so many robots on the realistic level due to problems of cost, storage facility, transportation and person who have operational skill.

Therefore, we give considerable attention to module robot, because we can appropriately change the form of module robot. In the last few decades, the literature on the module robots has flourished with numerous proposed approaches to developed and control [7, 8]. However, the module robot basically consists of only joint modules. Therefore, applications of the module robot are limited until now.

We have proposed multi-purpose module system (MMS) which consist of joint modules and function modules. It is possible to transform the MMS such as series-connected form, quadruped form and so on. This is an advantage for unknown situation, because we can change the MMS to the appropriate form with sensors after arrived at disaster sites.

We have developed several types of modules which are joint modules, sensor modules and communication modules and proposed series connected form MMS (MMS-C02). And we have evaluated locomotion methods which are meandering and twisting [9]. The results showed that the MMS-C02 moved on the flat floor. The advantage of the MMS-C02 is for narrow space and fragile land moving. However, the MMS-C02 is totally unsuited for the irregular terrain such as stairs and high vertical interval.

In this paper, we propose a quadruped form MMS (MMS-G02). Trajectory of the leg of the MMS-G02 is evaluated by simulation. Controlling of an inverted pendulum is widely studied [10, 11]. Therefore, we apply the inverted pendulum model to the MMS-G02 and control the MMS-G02 using a state feedback control to stay in balance. And the effect of friction force between the MMS-G02 and the ground is investigated by simulation.

2 MMS

2.1 Characteristics of modules

We have developed several types of modules which are joint, camera, sensor, communication, divergence and toe modules. Details of each module are as follows.

Joint module (JS11-02, JU11-03): The joint modules have one or more active joints to generate the motion. They are mainly composed of DC motor or servomotor, and angle sensors.

Camera module (SC01-03): The camera module have camera for robotic vision to receive surrounding environments. Normally, the camera module is attached on the head of the robot.

Sensor module (SA11-01): The sensor module has several sensors, such as acceleration, gyro, earth magnetism and GNSS, to calculate the attitude and position of the module. And these sensors may be used for 3D self-location estimation.

Communication module (CB10-01): The communication module is main module which issue order to all the other modules. And this module communicates with not only other modules, but also PC and controller.

Divergence module (DC32-03, DC41-04): The divergence module has multiply connecting port to other modules. These are developed for multi-legged form MMS. DC32-03 and DC41-04 have the same function except connector type. DC32-03 has three male connectors and two female connectors. DC41-04 has four male connectors and one female connector.

Toe module (TS01-03): Toe module has passive joints to properly contact to the ground. This module is also especially developed for multi-legged form MMS.

Each module has a microcontroller which control the module individually and a battery. For the communication between the modules, we used CAN communication because of high resistance to noise. Basic size of all modules is set to ϕ70mm.

Connection method of the modules each other is only two steps; push the bottom and then give module a turn to the right. The electrical connections also are done by this method at the same time, and the MMS recognized own form, automatically. Therefore, we can change the form of MMS without special technic.

2.2 Quadruped form of MMS (MMS-G02)

The legged robot is suited for the irregular terrain such as stairs and high vertical interval. Therefore, we propose new form of the MMS which is the quadruped form MMS (MMS-G02). Photograph and specification of the MMS-G02 are shown in **Fig.1** and Table 1, respectively. Composed modules of the MMS-G02 are 8 types and total 17 modules as shown in Table 2. The joint modules (JS11-02 and JU11-03) and the toe module (TS01-03) are used for one leg. Therefore, each leg has 3 degree of freedom (DOF) as active joint and 2 DOF as passive joint. The senor module (SA11-01) is located on the center of the MMS-G02.

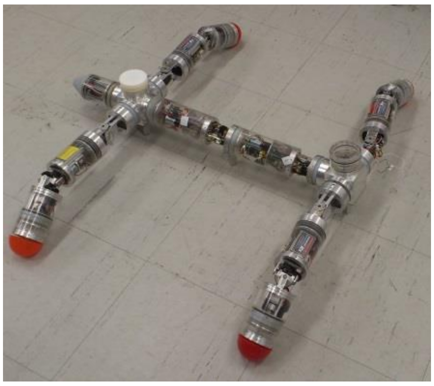


Fig. 1 MMS-G02

Table 1 Specification of MMS-G02

size[mm]	width	847
	length	741
	height	220
weight[Kg]		7.28
Number of legs		4
DOF per one leg		3

Table 2 Specification of composed modules

Module name	Size [mm]	weight [g]	DOF	Num ber
JS11-02	$\phi70\times122$	350	1	4
JU11-03	$\phi70\times302$	700	2	4
SC01-03	$\phi70\times85$	230	0	1
SA11-01	$\phi70\times100$	250	0	1
CB10-01	$\phi70\times135$	320	0	1
DC32-03	93×103×94	640	0	1
DC41-04	93×103×84	640	0	1
TS01-03	$\phi70\times80$	250	2	4

3 Model of gait

In this paper, we apply trot gait to the MMS-G02, since these gait is widely used for the quadruped robots.

In this case, it is important to control the attitude of legged robot due to the unstable stand. Thus, we applied the inverse kinematics to determine the each leg position and the state feedback control for the stability gait control.

3.1 Inverse kinematic analysis for MMS-G02

MMS-G02 has 3 DOF for each leg, one is on the base $P_1(x_1, y_1, z_1)$ (yaw direction, 1st joint) and the others are on the middle $P_2(x_2, y_2, z_2)$ (roll and pitch direction, 2nd joint), as shown in **Figs. 2-4**. **Figures 2-4** show the mechanism of right front leg. Here, y axis is a direction of toward movement, x axis is a direction of perpendicular to the y axis on the horizontal plane and z axis is direction of perpendicular to the x-y plane. Used parameters are defined as follows, $L_{ik,1}$, $L_{ik,2}$, $L_{ik,3}$, are distances between 1st joint P_1 and 2nd joint P_2, 2nd joint P_2 and toe P_3 and 1st joint P_1 and toe P_3, respectively, θ_{yaw} is angle of yaw direction at the 1st joint, θ_{pitch} is angle of pitch direction at the 2nd joint and θ_{roll} is angle of roll direction at the 2nd joint.

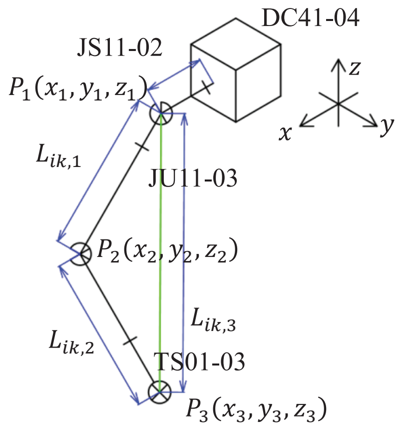


Fig. 2 Mechanism of right front leg of MMS-G02

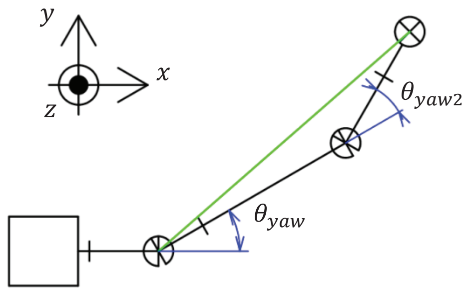


Fig. 3 Mechanism of right front leg in x-y plane

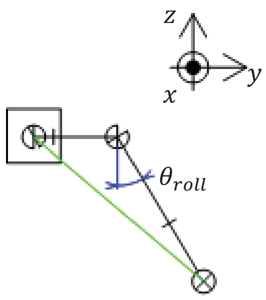


Fig. 4 Mechanism of right front leg in y-z plane

From the joint angles and distances between the joints and the toe, the position coordinates of the toe $P_3(x_3, y_3, z_3)$ is calculated as follows,

$$x_3 = L_{ik,1}\cos\theta_{yaw} + L_{ik,2}\cos(\theta_{yaw} + \theta_{yaw2}) \tag{1}$$

$$y_3 = L_{ik,1}\sin\theta_{yaw} + L_{ik,2}\sin(\theta_{yaw} + \theta_{yaw2}) \tag{2}$$

$$z_3 = -L_{ik,2}\cos\theta_{roll}\cos\theta_{pitch} \tag{3}$$

$$\theta_{yaw2} = \tan^{-1}\frac{\sin\theta_{pitch}}{\sin\theta_{roll}} \tag{4}$$

Here, the position of the 1st joint $P_1(x_1, y_1, z_1)$ is defined as origin to simplify the equation of calculation and θ_{yaw2} is composed by θ_{roll} and θ_{pitch}. Thus, the joint angles can be calculated by using the inverse kinematics,

$$\theta_{yaw} = \tan^{-1}\left(\frac{y_3}{x_3}\right) - \cos^{-1}\left(\frac{{L_{ik,1}}^2 + {x_3}^2 + {y_3}^2 - {L_{ik,2,2}}^2}{2L_{ik.1}\sqrt{({x_3}^2+{y_3}^2)}}\right) \tag{5}$$

$$\theta_{roll} = \cos^{-1}\left(\frac{-z_3}{L_{ik,2}\cos\theta_{pitch}}\right) \tag{6}$$

$${L_{ik,2,2}}^2 = {L_{ik,2}}^2(1 - \cos^2\theta_{roll}\cos^2\theta_{pitch})$$

To determine the joint angles, we define that the θ_{pitch} is constant, because we use the θ_{pitch} as the input for stable control. **Figure 5** shows an example of the calculated joint anglesθ_{roll}, θ_{yaw} during a swing phase. In **Fig. 5**, specific predefined parameters are as follows, angleθ_{pitch} is 0 rad, maximum high of toe is 50 mm, elevating speed is 100 mm/s, travel distance per 1 period is 400 mm and moving speed is 200 mm/s.

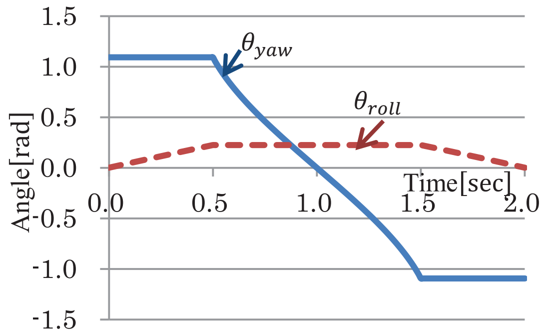


Fig. 5 Joint angles during a swing phase

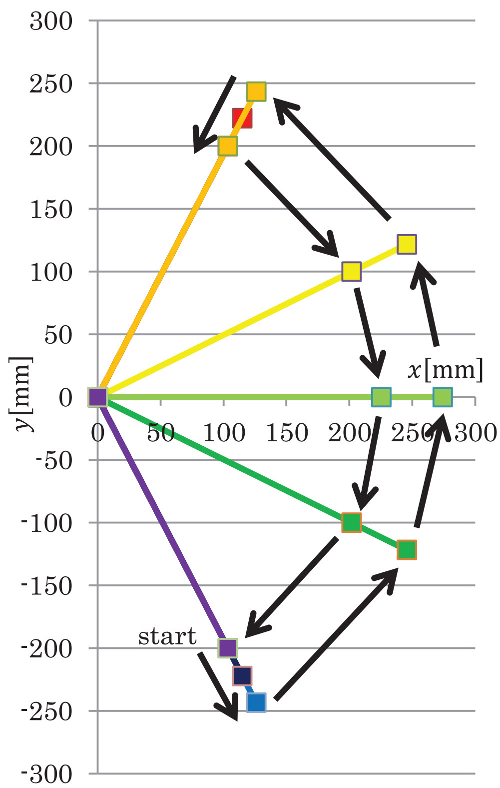


Fig. 6 Trajectory of leg in x-y plane

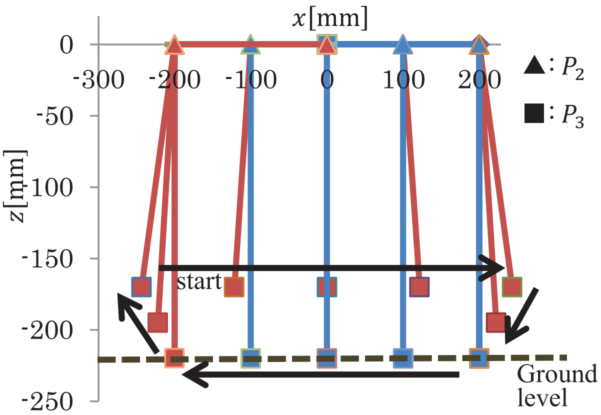


Fig. 7 Trajectory of leg in x-z plane

In case of **Fig. 5**, we can calculate the trajectory of the leg in x-y and x-z planes as shown in **Figs. 6** and **7**, respectively. Ground level is $z = -220$ mm. The results show that the leg is properly moved without collisions. The maximum angle of idling leg, which is 0.22 rad is observed from the trajectory of the leg.

3.2 Stability gait control

In case of the crawl gait, there are three or more support legs. Additionally, a center of the gravity is located in the center of the MMS-G02. Therefore, even during the moving, the center of the gravity is located in space bounded by support legs, regardless of the cause the idling leg. Thus, the MMS-G02 is statically stable. As a result, it is not necessary to stability control in the crawl gait.

In case of the trot gait, there are only two support legs. It means the MMS-G02 is unstable. Therefore, we have to control the attitude of the MMS-G02.

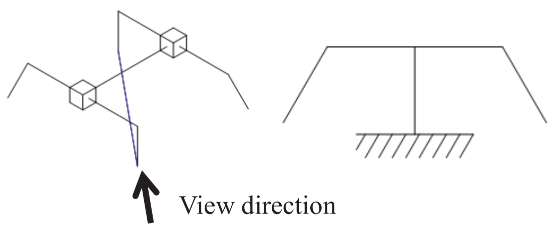
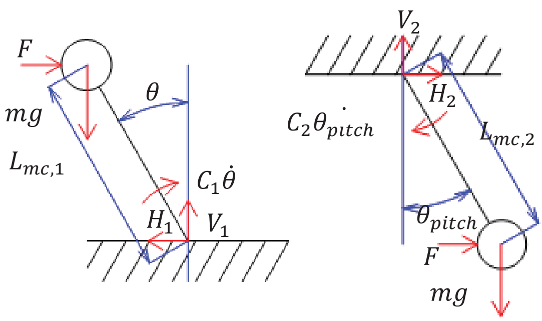


Fig. 8 Model of MMS-G02



(a) **(b)**

Fig. 9 Detail of the pendulum model of MMS-G02

We propose a way of model of two legs standing for the MMS-G02. In the state of two legs standing, the MMS-G02 is similar to an inverted pendulum when we look at the MMS-G02 from arrowed view direction, as shown in **Fig.8**. Therefore, the MMS-G02 is composed of the inverted pendulum where is below the position of the center of the gravity as shown in **Fig. 9**(a) and the pendulum where is above the position of the center of the gravity as shown in **Fig. 9**(b). In **Fig. 9**, θ is a lean of the MMS-G02, θ_{pitch} is the joint angle, m is the mass of the MMS-G02, g is acceleration of the gravity, F is the applied force, which include the effect of acceleration, to the pendulum, V_1, V_2, H_1, H_2 are reaction forces for the horizontal and the vertical directions, C_1 and C_2 are friction coefficients between sole and ground and shaft and bearing of 2nd joint, respectively, and $L_{mc,1}$ and $L_{mc,2}$ are distances from the origin to the center of the gravity. θ is uncontrollable parameter and $\theta_{yaw,2}$ is controllable parameter in the MMS-G02.

Newton's equations of the motion of the MMS-G02 in **Fig. 9**(a) and (b) are expressed as eqs. (7) to (9) and (10) to (12), respectively.

$$I_1\ddot{\theta} = V_1 L_{mc,1}\sin\theta - H_2 L_{mc,1}\cos\theta + C_1\dot{\theta} \quad (7)$$

$$mD^2\left(L_{mc,1}\sin\theta + L_{mc,2}\sin\theta_{pitch}\right) = H_1 + F \quad (8)$$

$$mD^2\left(L_{mc,1}\cos\theta + L_{mc,2}\cos\theta_{pitch}\right) = V_1 - mg \quad (9)$$

$$I_2\ddot{\theta}_{pitch} = V_2 L_{mc,2}\sin\theta_{pitch} - H_2 L_{mc,2}\cos\theta_{pitch} + C_2\dot{\theta}_{pitch} \quad (10)$$

$$mD^2\left(L_{mc,1}\sin\theta + L_{mc,2}\sin\theta_{pitch}\right) = H_2 + F \quad (11)$$

$$mD^2\left(L_{mc,1}\cos\theta + L_{mc,2}\cos\theta_{pitch}\right) = V_2 - mg \quad (12)$$

$$I_1 = \frac{mL_{mc,1}{}^2}{3}, I_2 = \frac{mL_{mc,2}{}^2}{3}, D^2 = \frac{d}{dt^2}$$

From the eqs. (7) to (12), we can observe following equations:

$$\begin{aligned}&\ddot{\theta}\left(I_1 + mL_{mc,1}{}^2\right)\\&+\ddot{\theta}_{pitch} mL_{mc,1}L_{ik,2}\cos\left(\theta - \theta_{pitch}\right)\\&+\dot{\theta}_{pitch}{}^2 mL_{mc,1}L_{mc,2}\sin\left(\theta - \theta_{pitch}\right)\\&-mgL_{mc,1}\sin\theta - C_1\dot{\theta} = FL_{mc,1}\cos\theta\end{aligned} \quad (13)$$

$$\begin{aligned}&\ddot{\theta}_{pitch}\left(I_2 + mL_{mc,2}{}^2\right)\\&+\ddot{\theta} mL_{mc,1}L_{mc,2}\cos\left(\theta - \theta_{pitch}\right)\\&-\dot{\theta}^2 mL_{mc,1}L_{mc,2}\sin\left(\theta - \theta_{pitch}\right)\\&-mgL_{mc,2}\sin\theta_{pitch}\\&-C_2\dot{\theta}_{pitch} = FL_{mc,2}\cos\theta_{pitch}\end{aligned} \quad (14)$$

Using the eqs. (13) and (14), the state equation of the MMS-G02 is expressed as eq. (15).

$$x = A\dot{x} + bF \tag{15}$$

$$x = \begin{bmatrix} \theta \\ \theta_{pitch} \\ \dot{\theta} \\ \dot{\theta}_{pitch} \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ b_3 \\ b_4 \end{bmatrix}$$

$$a_{31} = -(I_2 + mL_{mc,2}{}^2)mgL_{mc,1}/\alpha 0$$
$$a_{32} = m^2 gL_{mc,1}L_{mc,2}{}^2/\alpha 0$$
$$a_{33} = (I_2 + mL_{mc,2}{}^2)C_1/\alpha 0$$
$$a_{34} = mL_{mc,1}L_{mc,2}C_2/\alpha 0$$
$$a_{41} = m^2 gL_{mc,1}{}^2 L_{mc,2}/\alpha 0$$
$$a_{42} = -(I_1 + mL_{mc,1}{}^2)mgL_{mc,2}/\alpha 0$$
$$a_{43} = mL_{mc,1}L_{mc,2}C_1/\alpha 0$$
$$a_{44} = (I_1 + mL_{mc,1}{}^2)C_2/\alpha 0$$
$$b_3 = (I_2 + mL_{mc,2}{}^2)L_{mc,1} - mL_{mc,1}L_{mc,2}{}^2/\alpha 0$$
$$b_4 = (I_1 + mL_{mc,1}{}^2)L_{mc,2} - mL_{mc,1}{}^2 L_{mc,2}/\alpha 0$$
$$\alpha 0 = I_1 I_2 + I_1 mL_{mc,2}{}^2 + I_2 mL_{mc,1}{}^2$$

4 Results and discussion

Using eq. (15), behavior of the MMS-G02 can be calculated. Simulation conditions are m = 7.68kg, $L_{mc,1}$ = 0.1884m, $L_{mc,2}$ = 0.0316m, C_1 = 0.01 and C_2 = 0.01, which are measured values.

Figure 10 shows impulse responses (input: F) for angles, θ and $\theta_{yaw,2}$, without the stability control. The results show that the MMS-G02 fall to the ground at 3s. Therefore, we apply the MMS-G02 to the state feedback control to stay in balance.

We calculate the feedback gains by using Matlab. And obtained feedback gains are as follows,

$$F = [482.1305 \;\; 0.2362 \;\; -0.6419 \;\; -5.3132] \tag{16}$$

Using these feedback gains, we recalculated the angles. **Figure 11** shows the angle θ as a function of the time at condition of C_1 = 0.1, 0.01 and 0.001, respectively. **Figure 11** show that the θ is converged to the 0 at all conditions. It is indicated that the MMS-G02 can be stably controlled. The results also indicated that the maximum angle of θ is 0.14 rad which is smaller than the maximum angle of idling leg, 0.22 rad. Thus, the MMS-G02 can stay in balance and keep on the two legs.

Figure 12 show that the maximum amplitude and the over shoot of θ as a function of the friction coefficient C_1. The maximum amplitude decreases with increasing the friction coefficient. Therefore, the large friction coefficient is more stable than the small one. However, the overshoot decreases with increasing the friction coefficient. Thus, there is possibility become unstable control due to the oscillation.

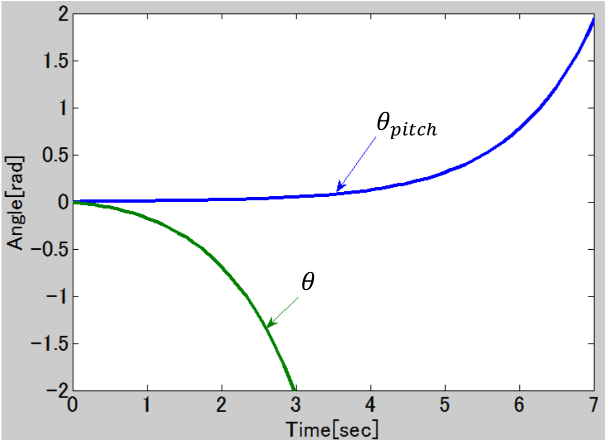


Fig. 10 Behavior of attitude of MMS-G02 without control

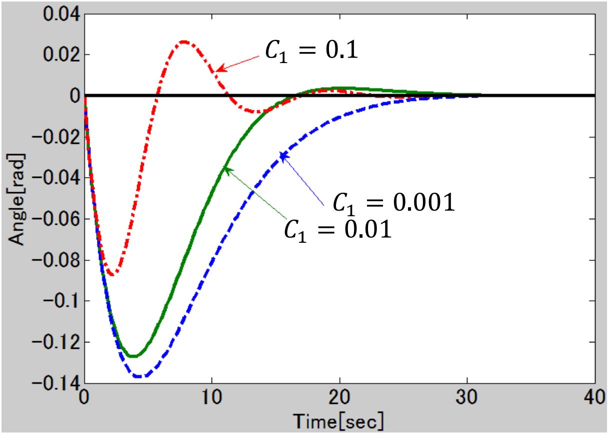


Fig. 11 Behavior of attitude of MMS-G02 with control

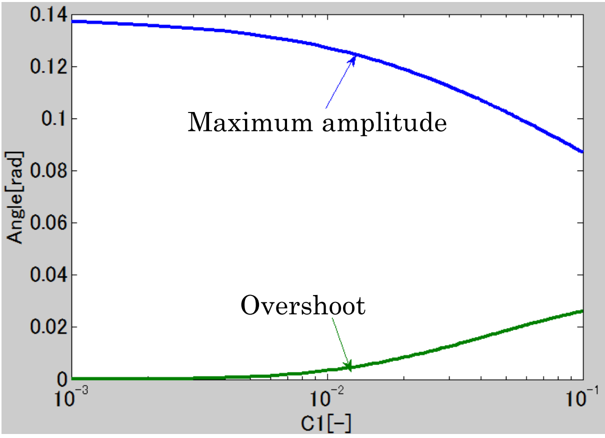


Fig. 12 Effect on the friction coefficient

5 Conclusions

In this paper, the Multi-purpose Module System, MMS, was developed. Developed MMS consist of joint modules and function modules. Therefore, the MMS can change the form such as series-connected form, quadruped form and so on. This is an advantage for unknown situation, because we can change the MMS to the appropriate form and add the sensors after arrived at disaster sites.

The quadruped form the MMS, MMS-G02, was also developed. And the modeling and the simulation of the MMS-G02 was discussed.

We applied the inverse kinematics to determine the each leg positions. From the inverse kinematics, the trajectory of the leg of the MMS-G02 was evaluated by simulation. The leg was properly moved and the maximum angle of idling leg was 0.22 rad.

We proposed the inverted pendulum model and controlled the MMS-G02 using the state feedback control to stay in balance. And the effect of the friction force between the MMS-G02 and the ground was evaluated by simulation. The maximum value of the lean of the MMS-G02 θ was 0.14 rad which was smaller than the maximum angle of idling leg. The results indicated that the MMS-G02 can stay in balance and keep on the two legs.

We believe the proposed calculation model is useful in achieving control of the MMS-G02 to adapt a changing environment. In the future work, the proposed model of stability control will be extended to the effective walking of the MMS-G02.

Acknowledgement

The present work was partially supported by a special research grant from Aichi Institute of Technology, Japan.

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Received on October 31, 2013
Accepted on January 28, 2014