Design of Multilayered Suspension Mechanism for Differential Type Mobile Robot

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Abstract: This paper presents a design for the novel suspension mechanism of a two-wheeled mobile robot having two casters which is used for indoor environment. Although the indoor environment is less rough than the outdoor one, the fixed caster mechanism has some problems such as causing the robot to be immovable because robot's driving wheels do not have contact with the ground. Therefore, we tried installing a spring-damper suspension mechanism to keep driving capability and to remove pitching phenomenon. However, this suspension mechanism also has the problem, which the robot body inclined by disturbances does not return to the initial position. To deal with above problems and to accomplish desired performances, we designed the *Multilayered Suspension Mechanism*, which has springs and dampers working partially according to the inclined angle and angular velocity of robot body concerned with pitching. To analyze design, the equations of motion describing their dynamics were developed. Using the equations, simulation results show the improved performance. We confirm the usefulness of the *Multilayered Suspension Mechanism* by construction and test of a actual prototype.

Keywords: Two wheeled mobile robot, Differential steering, Multilayered suspension mechanism

1. Introduction

So far, many mobile robot researchers have studied in various sections for the application in the real world. The study on the mobility of mobile robots are fundamental and important. However, most of them bring focus into the automatism of the suspension mechanism and the development of the special mechanism for traveling over rough terrain [1] [2]. Their general application in human living environment requires increased complexity, size, and cost. Economical efficiency as well as a desired performance should be considered in the development of indoor mobile robots. This paper presents the novel suspension mechanism of the two wheeled mobile robot with differential steering type to maintain dynamic stability and satisfy requests. For the locomotion of mobile robots, the differential steering type with two wheels is popular because of simple mechanism, energy efficiency, etc [9]. It However needs a few caster to provide reaction force to keep stability. We have used the same type for above these benefits. To be more particular, our mobile robot has two driving wheels in the middle of robot body and is equipped with a caster respectively in the front and the rear [4]. In real driving experiment, We found some important consideration factors as follows.

The first, the environment in which mobile robot drives in is not perfectly flat, there is unevenness even if it is indoor space, for example, doorsills, high and low of floor. These height is generally 1 $\sim$ 2 cm. The second, the driving capability in the uneven ground is dependant on the size of equipped casters. the higher unevenness is, the bigger the size of caster is. The third, the caster and driving wheel mechanism which has fixed casters at the bottom of the robot body (abbreviated as fixed caster mechanism) can not absorb the shock which arises when a mobile robot travels over uneven ground and raise a problem in internal electric circuits, mechanical joints and the endurance of parts. The fourth, a fixed caster mechanism is opt to cause the robot to be immovable. It is unable to climb a slope because robot's driving wheels can not have contact with the ground. The last, to maintain dynamic stability of mobile robot is dependant on the relation between the feature of mobile robot and the equipped position of caster. If the mobile robot is taller, its center of mass moves up and dynamic stability is affected by inertia force when mobile robot starts or stops suddenly or collides with low obstacle not to go over. To preserve enough stability, a caster must be equipped at a long distance from the center axis of a mobile robot. However, this is not a good choice because of the restricted turning space of the mobile robot. Therefore, we tried to design the suspension mechanism of mobile robot to obtain desired performances considering the above statements. In this process, we were able to find some problems of prototypes and we developed a novel *Multilayered Suspension Mechanism* in the end. In the section 2, we will describe problems which the existing suspension mechanisms have, and to deal with this problems, present the design of the *Multilayered Suspension Mechanism*. We will show simulation results to prove the usefulness of this mechanism in the section 3.

2. Design of Multilayered Suspension Mechanism

2.1. Problems of Fixed Caster Mechanism

First, we disuss problems which fixed caster mechanism, along with the general equations of motion describing their dynamics. In fixed caster mechanism, to investigate factors which affect mobile robot's stability, general equations of motion were developed for whole mobile robot system.

The some assumptions are as follows.

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• The wheels don't skid at all and the mobile robot is regarded as a system without drift [5].
• The mobile robot's total mass is regarded as concentrating on a center of mass.
• The disturbances which affect the mobile robot are the height difference transmitted from the ground to casters and wheels, and inertia forces applied on a center of mass.

So, considering above assumptions, the simple model of two-caster and two-wheeled mobile robot is as Fig. 1. The dynamic model is regarded as having rotational motion with 1 degree of freedom in z-axis. The system model of whole mobile robot with the fixed caster suspension mechanism is as Fig. 2. The problem which the fixed caster mechanism has shown in Fig. 3when a mobile robot climbs slope. The mobile robot can not clamber the slope because robot's driving wheels do not have contact with the ground. Based on Fig. 4, we can obtain general equation of motion to evaluate dynamic stability and performance in extreme condition, that is, the excessive reaction force works on mobile robot's center of mass. The mobile robot collides with the projection of the ground and turn around front caster due to reaction force. From this, we can get a equation of motion.

$$F(H + L_f \sin\theta) = W(L_f - H\sin\theta) \tag{1}$$

where, F is a inertia force exerted on center of mass by reaction force and W is the weight of mobile robot. L_f, H is respectively the distance from driving wheel to front caster, the distance from front caster to a center of mass. θ is the angle which robot leans to front side. To maintain robot's dynamic stability, the condition of equation 2 must be satisfied and the rearrangement of equation 1, become equation 3.

$$L_f - H\sin\theta \geqq 0$$
$$\theta \leqq \arcsin(\frac{L_f}{H}) \tag{2}$$
$$\theta = \arcsin(\frac{L_f}{H} - \frac{F}{W}) \tag{3}$$

where, $F = m \cdot a$, $W = M \cdot g$. g is the gravity acceleration, a is the acceleration by reaction force.

So, we should design the mechanism paying due regard to equation 2 and 3. In section 3, using equation 2 and 3, we will compare the stability of fixed suspension mechanism with others.

To deal with the problem which a mobile robot can not climb a slope because driving wheels do not have contact with the ground, we designed the caster mechanism to change its elevation with spring. This changeable caster mechanism allow the driving wheel to have always contact with the ground. Besides, the shock energy transmitted from unevenness to robot body is absorbed and robot can climb the higher ground obstacle with same caster size than the fixed caster mechanism. However, in changeable caster suspension mechanism using only spring, the body pitching, that is, vibration about driving wheel axis, is continued for long time, and in serious case, the stability of the robot can be destroyed, and so robot could capsize. This problem may

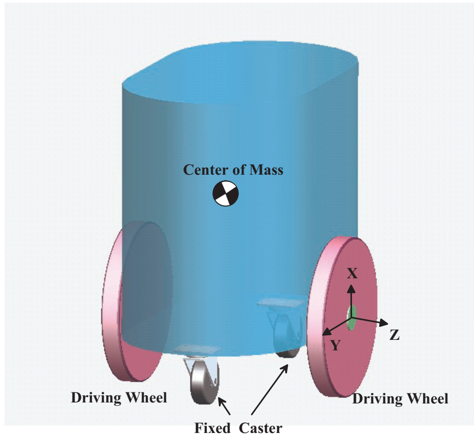

Fig. 1. Construction of a fixed two-caster and two-wheeled Mobile Robot

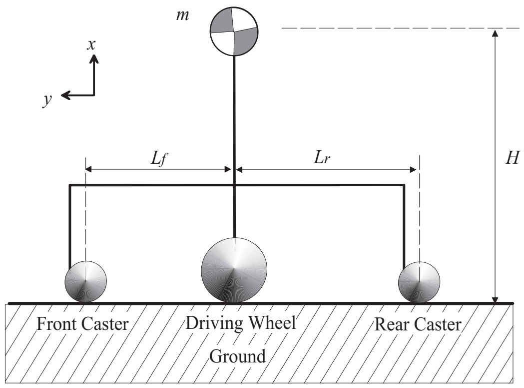

Fig. 2. System model of fixed caster-mobile robot

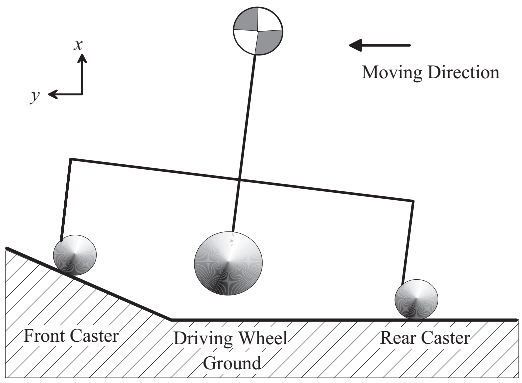

Fig. 3. Problem example of fixed caster-mobile robot

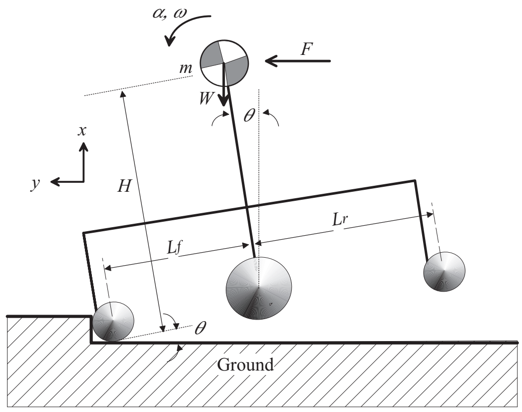

Fig. 4. Dynamic model when crash

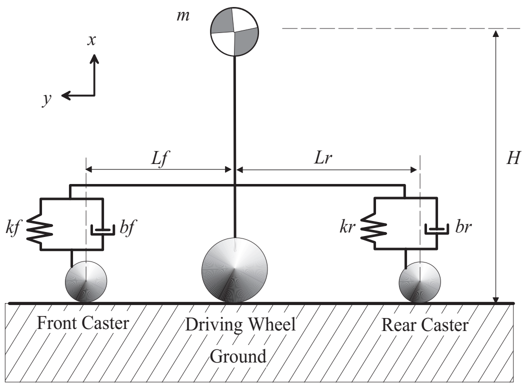

Fig. 5. System model of robot with the spring-damper suspension mechanism

be more serious to tall robots. Therefore, we adopted the spring-damper suspension mechanism to change a elevation of caster and to dissipate vibration energy.

2.2. Spring-Damper Suspension Mechanism

To cope with the problem of the fixed caster mechanism, we installed spring and damper with critical damping coefficient respectively on front caster and rear caster as Fig. 5. The spring is initially compressed by robot's weight. Because of it, when a robot travels over the ground which the height of the ground becomes low in robot's driving direction, casters can have contact with the ground. In this condition, the compressed spring is extended. When a mobile robot encounters a slope in moving direction and climbs it, a spring-damper suspension mechanism works as Fig. 6. The springs on the front and rear casters are compressed properly, and the dampers dissipate rest energy except for potential energy of springs. Using this mechanism, the dynamic stability and performance of a mobile robot which has spring-suspension mechanism are studied. Fig. 7 shows the case in which robot's stability may be destroyed. The mobile robot collides with a projection of the ground and leans to front side centering driving wheels due to reaction force. To analyze dynamic performance, the bondgraph of the robot system in Fig. 7 is obtained as Fig. 8. From bondgraph, we developed state-space equation as equation 4. To linearize equation, We assume that robot body is inclined by maxium $\theta = 9$ degree and this assumption is appropriate as mentioned the first consideration in section 1. Hence, sin $\theta \cong \theta$, cos $\theta \cong 1$.

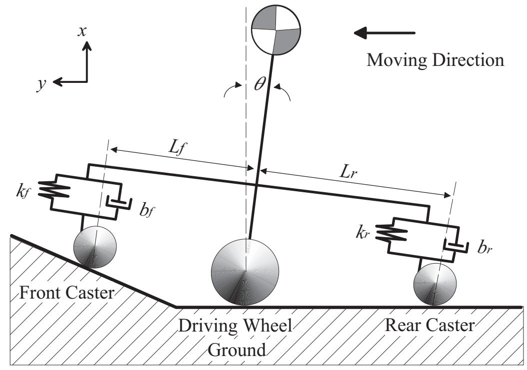

Fig. 6. Application example using the spring-damper suspension mechanism

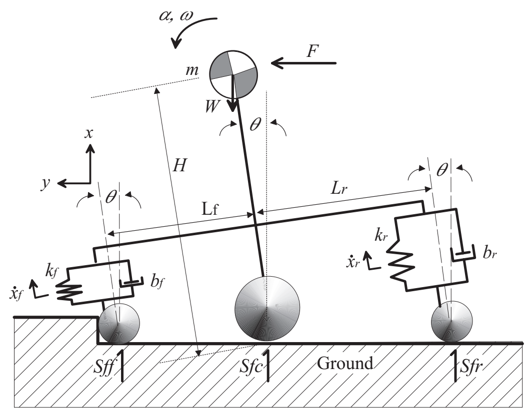

Fig. 7. System model including input sources

$$\frac{d}{dt}\begin{bmatrix}\theta\\ h\\ x_f\\ x_r\end{bmatrix} \tag{4}$$

$$= \begin{bmatrix} 0 & \frac{1}{J} & 0 & 0\\ MgH & -(\frac{b_f L_f^2}{J} + \frac{b_r L_r^2}{J}) & L_f \cdot k_f & -L_r \cdot k_r\\ 0 & \frac{-L_f}{J} & 0 & 0\\ 0 & \frac{L_r}{J} & 0 & 0 \end{bmatrix}\begin{bmatrix}\theta\\ h\\ x_f\\ x_r\end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 & 0\\ 1 & L_f b_f & -L_r b_r\\ 0 & 1 & 0\\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} MaH\\ S_{ff} - S_{fc}\\ S_{fr} - S_{fc}\end{bmatrix}$$

where, J is the moment of inertia about point which driving wheels have contact with the ground and k_f, k_r, b_f, b_r are respectively spring constants and damping coefficients of the

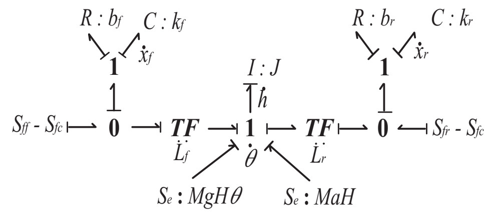

Fig. 8. Bondgraph of robot with the spring-damper suspension mechanism

front and rear caster. Others are defined same with fixed caster mechanism. Front caster's displacement x_f and rear caster's displacement x_r are respectively

$$x_f = -x_{fi} + \Delta x_f$$
$$x_r = -x_{ri} + \Delta x_r$$

where, x_{fi} and x_{ri} are initial compressed displacement of the front and rear casters. The input sources shown in Fig. 7 are a inertia force (Ma) and a robot's weight(Mg) as the effort source. S_{ff}, S_{fc} and S_{fr} mean respectively the differential values of elevation which are transmitted from uneven ground to the front caster, driving wheels, and rear caster. The relative values among S_{ff}, S_{fc} and S_{fr} are inputed as the frow source to the front caster and rear caster. When a mobile robot leans to front side as θ, the displacement of spring Δx_f, Δx_r is function of θ as follows.

$$\Delta x_f = -L_f \cdot \theta$$
$$\Delta x_r = L_r \cdot \theta$$

The result of simulation using equation 3 for dynamic performance will be shown in section 3. Using this mechanism,we found a solution to the problem of the fixed caster mechanism. However, after robot body is slanted by disturbances, it is not returned to initial position(it is not $\theta = 0$ due to the eccentricity of caster, it is $\theta = 1.1$) because of coulumb friction in dampers. The actual damper has much friction force element in internal contact. It is a problem that the initial position is not original position($\theta = 0$). On this account, the mobile robot may be needed additional compensation tool or algorithm. We wanted it to return to $\theta = 0$ without pitching phenomenon fast and accurately. To amend above problems, we designed the *Multilayered Suspension Mechanism* introduced in next section.

2.3. Multilayered Suspension Mechanism

Though a spring-damper mechanism is partially successful design, we needed a effective mechanism which is returned accurately to original position without pitching phenomenon. Thus, we tried to design that damper, which is the main source of coulomb friction force, works partially and discontinuously if necessary and spring also works differently when extended or compressed. In detail, each damper (strictly speaking, shock absorber) works efficiently in the direction in which spring is compressed to resist disturbances and doesn't work in the direction in which spring is extended. Because a spring constant is bigger when compressed than when extended, more potential energy of a spring is absorbed in same displacement and less displacement arises according to same input source. Independently, the compressed damper is extended and returns to the initial position when load is removed. When robot body goes through the initial position and begins to incline to backward, the spring and damper on the rear caster are compressed. This locomotion is continued until returning to the initial position. Like this, because spring and damper works selectively according to inclined direction and angular velocity of the robot concerned

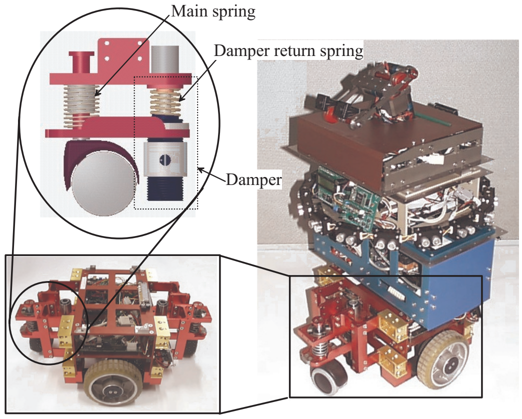

Fig. 9. Multilayered suspension mechanism

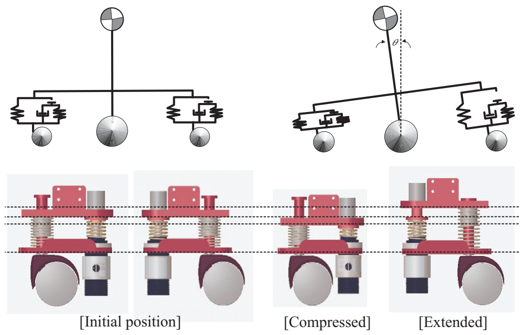

Fig. 10. Mechanism difference when compressed and extended

with pitching if necessary, we call this mechanism *Multilayered Suspension Mechanism*. Fig. 13 shows that the damper works only the partial section. Using this mechanism, the inclined robot body can return to the initial position more accurately than using spring-damper suspension mechanism. The design of *Multilayered Suspension Mechanism* is shown in Fig. 9. Fig. 10 and table 1 describe its locomotion. In table 1, $Spring_{f1}$, $Spring_{f2}$ and $Damper_f$ mean respectively the main spring, the damper return spring and the damper on the front caster, $Spring_{r1}$, $Spring_{r2}$ and $Damper_r$ mean respectively the main spring, the damper return spring and the damper on the rear caster. The system model of *Multilayered Suspension Mechanism* is shown in Fig. 11. To analyze dynamic performance of this mechanism, the bondgraph of mechanism is shown in Fig. 12. The equation 5 is a little different from the equation 4.

Table 1. Operation of multilayered suspension mechanism

Element	$\theta = 0$	$\theta > 0$		$\theta < 0$	
		$\dot{\theta} > 0$	$\dot{\theta} < 0$	$\dot{\theta} > 0$	$\dot{\theta} < 0$
$Spring_{f1}$	on	on	on	on	on
$Spring_{f2}$	off	on	off	off	off
$Damper_f$	off	on	off	off	off
$Spring_{r1}$	on	on	on	on	on
$Spring_{r2}$	off	off	off	off	on
$Damper_r$	off	off	off	off	on

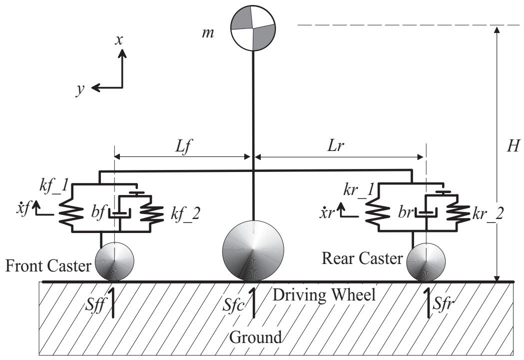

Fig. 11. System model of robot the multilayered suspension mechanism

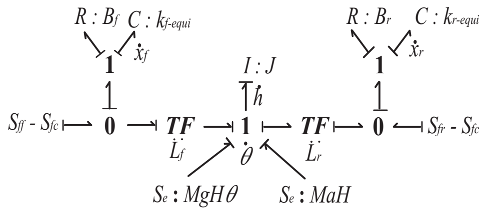

Fig. 12. Bondgraph of robot with the multilayered suspension mechanism

$$\frac{d}{dt}\begin{bmatrix}\theta\\ h\\ x_f\\ x_r\end{bmatrix} \tag{5}$$

$$= \begin{bmatrix} 0 & \frac{1}{J} & 0 & 0 \\ MgH & -(\frac{B_f L_f^2}{J} + \frac{B_r L_r^2}{J}) & L_f \cdot k_{fe} & -L_r \cdot k_{re} \\ 0 & \frac{-L_f}{J} & 0 & 0 \\ 0 & \frac{L_r}{J} & 0 & 0 \end{bmatrix} \begin{bmatrix}\theta\\ h\\ x_f\\ x_r\end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 & 0 \\ 1 & L_f B_f & -L_r B_r \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} MaH \\ S_{ff} - S_{fc} \\ S_{fr} - S_{fc} \end{bmatrix}$$

where, it is considered that springs and dampers work according to the inclined direction and angular velocity of robot body concerned with pitching. So, the equivalent spring constants k_{fe} and k_{re} and damping coefficients B_f and B_r are expressed as multiplication with Heaviside function as follows :

$$\begin{aligned} k_{fe} &= k_{f-1} + k_{f-2} H(-\Delta x_f) \cdot H(\dot{\theta}) \\ k_{re} &= k_{r-1} + k_{r-2} H(-\Delta x_r) \cdot H(-\dot{\theta}) \\ B_f &= b_f H(-\Delta x_f) \cdot H(\dot{\theta}) \\ B_r &= b_r H(-\Delta x_r) \cdot H(-\dot{\theta}) \end{aligned}$$

where, k_{f-1}, k_{f-2}, k_{r-1} and k_{r-2} are respectively the main spring constant of the front caster, the damper return spring constant of the front caster, the main spring constant of the rear caster and the damper return spring constant of the rear caster. $H(X)$ is heaviside function. the other parameters are defined as same with equation 4.

Table 2. Robot specification

Item	Content
Inertia (J)	1.539 kgm^2
Mass (m)	36.62 kg
Height of the center of mass	0.275 m
Length from body center to front caster (Lf)	0.2 m
Length from body center to rear caster (Lr)	0.252 m
Main spring constant of caster	1226 N/m
Damper return spring constant of caster	981 N/m
Damper coefficient of spring-damper suspension	568 Ns/m
Damper coefficient of multilayered suspension	4000 Ns/m

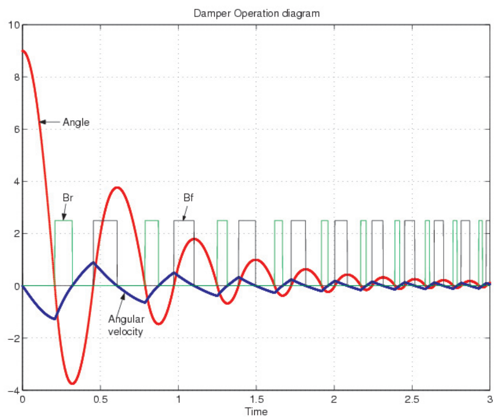

Fig. 13. Damper operation diagram

3. Simulation

Using the state-space equations obtained in Section 2, we simulate motion of mobile robot installed each suspension mechanism. MATLAB is used as simulation tool. Simulation conditions are defined as follows.

- Condition I

A mobile robot doesn't move and state variables are initially defined as [0.157, 0, -0.0314, 0.0395]. It means that in stop condition, a robot body is inclined as $\theta = 9$ degree and then front spring is compressed as 5.14cm and the rear spring is compressed as 1.95cm. Note springs were initially compressed by 2cm.

- Condition II

Initially a mobile robot runs in constant velocity 0.5m/s and it clashes a prominence of ground to be unable to climb, and then reaction force(F = 25.17 N) works on center of mass. The reaction force F is the multiplication of mass and acceleration when velocity reduce to zero during 0.2 second. The specification of the mobile robot is shown as table 2. According to each condition, simulation results are as Figs. 14 and 15.

Note that springs of casters initially were compressed by 2 cm. Thus, the mobile robot with spring-suspension mechanism is inclined to forward as 1.1 degree by the moment equilibrium caused by the eccentricity of caster axis. However, *Multilayered Suspension Mechanism* is not affected by the eccentricity of caster because inclined direction's spring

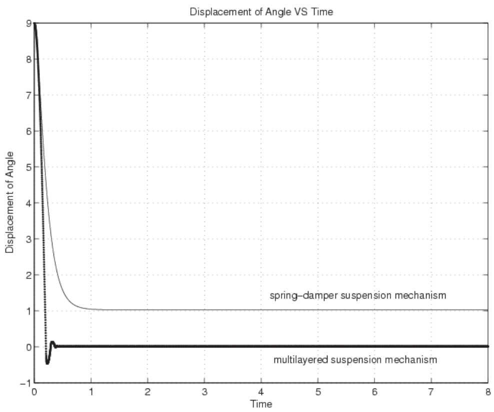

Fig. 14. Simulation result in condition I

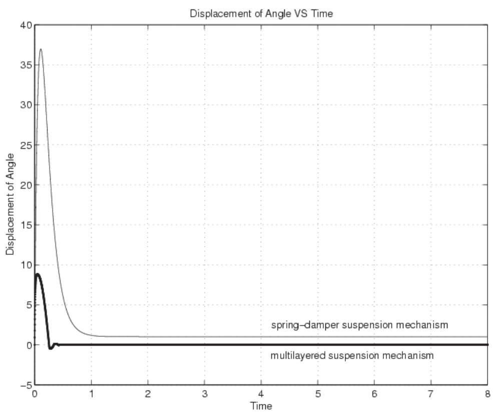

Fig. 15. Simulation result in condition II

constant is larger than the opposite. The graphs, which presented simulation results in each case, show that *Multilayered Suspension Mechanism* has improved response, compared to original spring-damper suspension mechanism. Specially, against inertia force's affection, it is more stable and has better performance : a short settle time and accurate return as shown in Fig. 15. It means that *Multilayered Suspension Mechanism* is robust against disturbances such as sudden start, sudden stop and crash. If the fixed caster mechanism receives the inertia force($F = 25.17\ N$), considering robot specification, robot's inclined angle is $\theta = 41.72$ degree. Even though this is in stable range, it is inappropriate response. Besides, In actual condition which coulomb friction force works, as *Multilayered Suspension Mechanism* has less section in which damper operates than spring-damper suspension mechanism, it can return to initial position more accurately.

4. Conclusion

In this paper, we presented the *Multilayered Suspension Mechanism* for the two-caster and two-wheeled mobile robot to maintain stability and to obtain improved performances. We have investigated the problems which existing fixed suspension mechanism has. To deal with the problems, we designed *Multilayered Suspension Mechanism*, which springs and dampers multilayeredly works according to incline direction and angular velocity of the robot concerned with pitching. Using this mechanism, mobile robot can always have efficient mobility and be protected from the shock of uneven ground. Moreover, robot body inclined by disturbances can return original position accurately. It doesn't need some complex mechanism, control algorithm or additional actuators.

5. Acknowledgements

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