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# Flexible Suspension Mechanism for Stable Driving of a Differential Drive Mobile Robot

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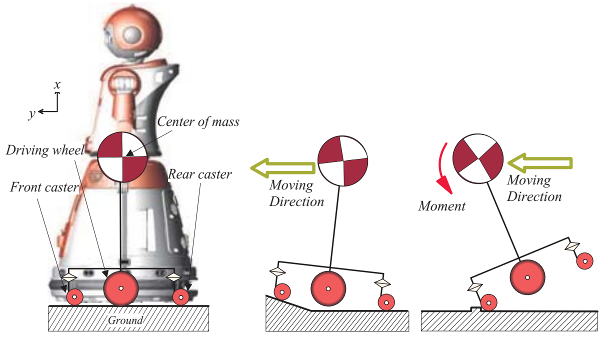
*Abstract*— **The differential drive mechanism, which is one of the mechanisms of wheeled mobile robots, is simple and useful for the motion of the mobile robot. The mechanism, however, has typical disadvantages of losing mobility, falling down, etc. when the robot moves over obstacles or uneven terrains. A novel suspension mechanism presented in this paper was designed to help the robot to overcome these problems. In particular, this mechanism is very suitable for a tall robot, which is susceptible to overturning because of the disturbance caused by acceleration, deceleration, and collision. The proposed mechanism called a *Multilayered Suspension Mechanism* is composed of the effective and well-directed combination of springs and dampers. It is very simple and cost-effective since it has no actuator for suspension. In this paper, mechanical construction and characteristics of the mechanism are described. Then, excellence and performance of the proposed mechanism are demonstrated by simulations and experiments.**



(a) (b) (c)

Fig. 1. Differential drive robot. (a) Schematic. (b) Losing of mobility in the uneven ground. (c) Falling down in the uneven ground

## I. INTRODUCTION

Differential drive is perhaps the simplest possible drive mechanism for a ground-contact wheeled mobile robot. A differential drive robot consists of two actively powered wheels, which is controlled by separate motors, and a couple of casters (idle wheels) to ensure the stability of the robot posture [1], [2]. The mechanism with two casters as shown in Fig. 1(a) is widely used because it can drive with comparatively good stability and allow zero-radius turns with a minimum wheel slip. When a robot with the differential drive mechanism is applied in a real environment, the efficiency of wheeled locomotion depends greatly on the flatness of the ground [3], [4]. Moreover, if the robot is tall, it is more necessary to have contact with the ground at all time because the robot can easily lose mobility or fall down on the uneven ground, as shown in Figs. 1(b) and 1(c). For this reason, some of the robots have suspension mechanisms using springs or spring-dampers to keep contact with the ground surface. Even though many studies have been focused on the development of special mechanisms for traveling over extremely rough terrain and on the active actuator-based automation of the suspension mechanism [5], few of suspension mechanism for the differential drive robot have been studied. When the mobile robot has a flexible suspension mechanism, the suspension absorbs vulnerable shocks as it moves on the uneven ground and can protect internal electric circuits and mechanical parts to enhance the reliability of the system.

In this paper, a new design of the suspension mechanism for the robot with two differential driving wheels and two additional casters is presented. The proposed mechanism called a *Multilayered Suspension*, which is not an active suspension system, is composed of the effective and well-directed combination of springs and a damper. The stability of the mobile robot, which is highly affected by the location of the center of gravity of the robot should be considered. The taller the mobile robot is, the more unstable it tends to be, especially when it makes a sudden start or stop.

In the next section, motivation of this study is presented. In Section III, the mechanical construction and the features of the proposed mechanism are described. Then, the performance and usefulness of the proposed mechanism are verified by simulations and by experiments. Finally, the authors conclude the paper.

## II. MOTIVATION

The spring-damper suspension is typical in automobiles. In the mobile robot, spring and damper systems can be installed on the front caster and the rear caster, as illustrated in Fig. 2. The springs are initially compressed with the weight of the robot. The spring and the damper absorb the disturbances from the ground when the robot moves over irregular surfaces. For example, the suspension of the front caster is compressed and the robot drives stably without the considerable changes of its posture when it crosses over a bump such as a doorsill in an instant, as shown in Fig. 2(a).

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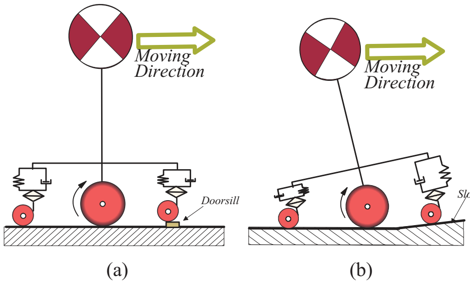


Fig. 2. Feature of the spring-damp suspension in differential drive robot. (a) Doorsill crossing. (b) Slope Climbing.

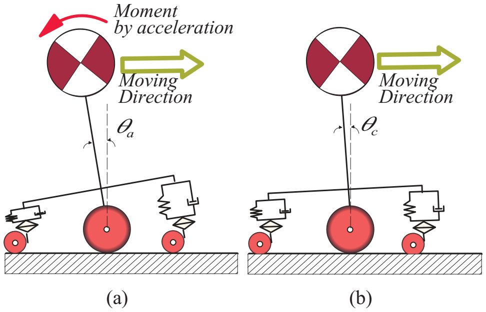


Fig. 3. Returning to initial posture after tilting by moment. (a) Moving state under acceleration. (b) Moving state under constant moving speed.

In case of slope climbing, the suspension of the front caster is extended and that of the rear caster is compressed. Thus, the driving wheels are forced to contact with the ground and the robot maintains its stability even though the robot is tilted, as shown in Fig. 2(b). However, there is still a problem in the spring-damper suspension mechanism. When the robot is tilted or inclined to one side as the tilting angle $\theta_a$ because of the moment, which is caused by acceleration (or deceleration), as shown in Fig. 3(a), it is unable to restore its initial posture even though the effect of the acceleration does not exist anymore as shown in Fig. 3(b); the angle $\theta_c$, which denotes the posture of the robot under a constant moving speed, is not zero. This is due to the nonlinearity and the coulomb friction in the dampers; the dampers behave differently when compressed and expanded. Moreover, since a damper for general suspension should be uni-directional to ensure the stable shock absorption, the difference is somewhat large. The authors did not recognize this problem when the suspension mechanism for our robot was under consideration at first. Actually, we have developed the robot using only the shock absorber, which is a suspension with a spring and a damper, as shown in Fig. 4 because most of vehicles have the mechanism based on only the shock absorber. As a result, this initial suspension mechanism for our differential drive robot was not successful.

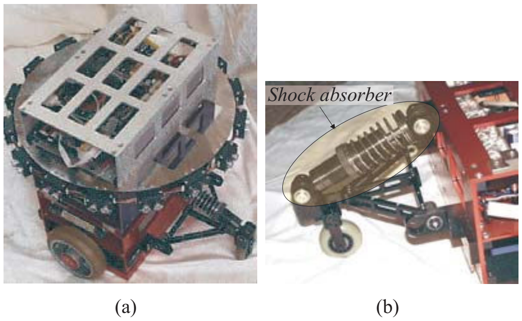


Fig. 4. Application example using the spring-damper suspension mechanism. (a) Full view. (b) Detail view.

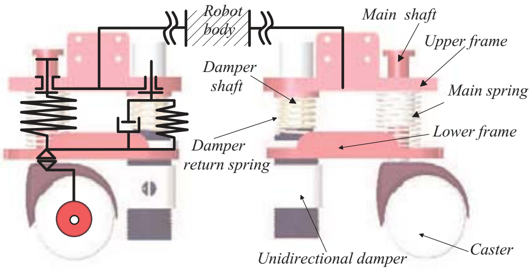


Fig. 5. Simple model of the proposed suspension mechanism.

In automobiles such as cars, the inclination is trivial in spite of such features of the damper because the weight is distributed and the height of the center of mass is low. In tall robots, however, the issue of restoring the initial posture is important. If the robot cannot compensate for the error of the inclination angle, it is difficult to successfully perform its tasks such as localization using vision and the data collection of the environment because of the inclined sensing-direction. Especially, since the appearance of the inclined robot does not provide the physical and visual comfort to users, commercial robots cannot accept such a mechanism. Thus, a mechanism should be developed to improve the typical spring-damper suspension such as the shock absorber. The problems of the spring-damper suspension mechanism can be resolved by reducing the effects of the nonlinearity and the frictions of the mechanical devices and parts in the dampers of the font and rear casters. However, it is practically and technically impossible to do so. In addition, even if the effects can be almost removed, very small inclination looks much large in tall robots. For this reason, the authors developed the mechanism so that it can make the robot restore the initial posture regardless of the nonlinearity and the frictions.

## III. MULTILAYERED SUSPENSION MECHANISM

In this section, the structure and working principle of the *Multilayered Suspension Mechanism* is described.

### A. *Overview of Mechanism*

The proposed mechanism has two caster assemblies, and the caster assembly is composed of a unidirectional damper, a main return spring, a damper return spring, an upper frame, a lower frame, shafts, etc, as shown in Figs. 5 and 6. The unidirectional damper, main shaft, and caster are fixed to the lower frame. The shock absorber, which is a subassembly of the damper and the damper return spring, works when compressed by a load. Reversely, at unloading, the compressed damper returns to its initial position by the damper return spring. The upper frame attached to the body of the mobile robot is coupled with the lower frame through

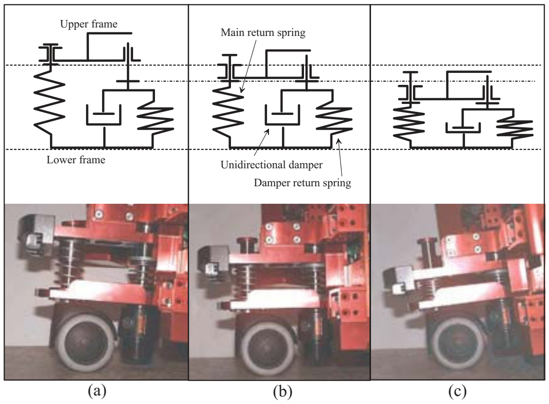


Fig. 6. Locomotion of proposed suspension mechanism. (a) Base position of each component without load by upper frame. (b) Initial position of each component under load by upper frame weight. (c) Compressed position of each component under load by disturbances.

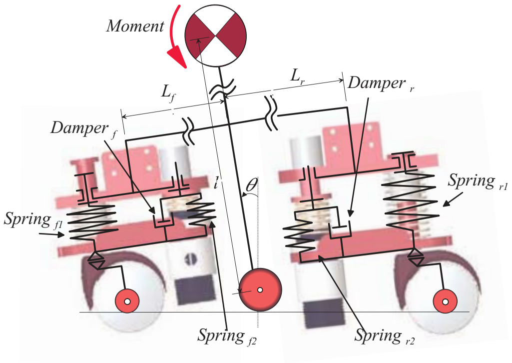


Fig. 7. When the robot body inclines to forward, the front caster assembly is compressed and the rear one is extended.

TABLE I

OPERATION OF *Multilayered Suspension Mechanism.*

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

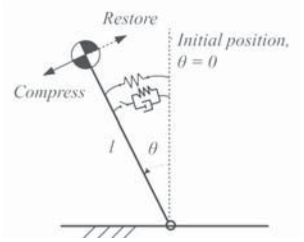


Fig. 8. Inverted pendulum model with the spring-damper.

the main shaft. The main return spring between the upper frame and lower one provides the reaction force proportional to the distance between the upper frame and the lower frame. Initially, the main spring is in the compressed state due to the weight of the robot. The upper frame contacts with the main return spring and the damper like the floating condition, as shown in Fig. 6(b).

### B. Working Principle

In the mobile robot depicted in Fig. 7, initially, suspension mechanisms in the front and the rear can preserve the home position (where the tilting angle $\theta = 0$) because of the moment equilibrium at the shaft of the driving wheels. Though the reaction force of the main return spring of the rear caster is larger than that of the front one due to the eccentricity of the caster, the total force of the main return spring and the damper return spring in the front caster keeps equilibrium with the force of the main return spring of the rear caster. Assuming that the robot is inclined toward the front side by disturbances as shown in Fig. 7, the upper frame floating on the spring and the damper begins to compress the main return spring, the damper return spring, and the damper in the front caster assembly. At this moment, only the main return spring of the rear caster assembly operates. If the disturbance disappears, the total spring force in the main return spring and the damper return spring operates to return the inclined robot toward the home position, and the damper restores its home position by the damper return spring. Even though the robot experiences an overshooting and is tilted backward, the inclined robot eventually returns to the home position by the action of the rear caster assembly similarly. In the proposed mechanism, the spring and the damper operate differently depending on the inclined direction and angular velocity of the robot with respect to the pitch angle. This is the core of the proposed suspension mechanism.

To sum up, the robot is attempt to restore the initial position by using the damper return spring; in addition, main return spring eliminates the effect by frictions and nonlinearity of the damper.

Table I summarizes how the components of the mechanism work in detail, where $Spring_{f1}$, $Spring_{f2}$ and $Damper_f$ denote the main spring, the damper return spring and the damper on the front caster, respectively. $Spring_{r1}$, $Spring_{r2}$ and $Damper_r$ denote the main spring, the return spring, and the damper on the rear caster, respectively.

### C. Dynamic Response Analysis

We model our robot as a simple inverted pendulum with the on-off torsional spring and damper according to the posture, as shown in Fig 8. Assuming that the condition of maintaining ground-wheel contact without moving (rolling or slipping), a simplified dynamic model of the system can be derived as (1).

$$\begin{array}{l} J\ddot{\theta} + Mgl\sin\theta = \tau \\ \tau = \tau_{ext} - \tau_k - \tau_d - \tau_f \end{array}, \tag{1}$$

where $J(= Ml^2)$ is the moment of inertia, $M$ is mass, $l$ is the length between the pivot point and the mass center, $g$ is the gravitational acceleration, $\tau_{ext}$ is the external torque, $\tau_k$ is the spring torque, $\tau_d$ is the damping torque, $\tau_f$ is the friction torque, and $\theta$ is the angle between the link and the vertical line.

The spring torque $\tau_k$ is given by

$$\begin{aligned}\tau_k &= (-F_f L_f + F_r L_r)\\ &= (K_f L_f + K_r L_r)\sin\theta \\ &\simeq K\theta,\end{aligned} \tag{2}$$

where $F_f$ and $F_r$ are the spring forces on the front and rear caster, $L_f$ and $L_r$ are the horizontal distances between the body center and the front and rear caster, as shown in Fig. 7. $K_f$ and $K_r$ are the spring stiffnesses of the front and rear caster, and $K$ is the total torsional spring stiffness. As in Equation (3), the three different spring stiffnesses are determined from the current robot posture $\theta$.

$$K = \begin{cases} (k_{f1}+k_{f2})L_f + k_{r1}L_r, & \theta > 0 \\ k_{f1}L_f + k_{r1}L_r, & \theta = 0 \\ k_{f1}L_f + (k_{r1}+k_{r2})L_r, & \theta < 0 \end{cases}. \tag{3}$$

The damping torque $\tau_d$ is given by

$$\begin{aligned}\tau_d &= (D_f L_f + D_r L_r)\cos\theta \cdot \dot{\theta} \\ &\simeq D\dot{\theta},\end{aligned} \tag{4}$$

where $D_f$ and $D_r$ are the damping coefficients of the front and rear caster. The suspension (damper) mechanisms are uni-directional with on-off mode, so that the damping coefficient is discrete-variable as the form

$$D = \begin{cases} d_f L_f, & \theta > 0,\ \dot{\theta} > 0 \text{ (Compress)} \\ 0, & \theta > 0,\ \dot{\theta} < 0 \text{ (Restore)} \\ 0, & \theta = 0,\ \dot{\theta} = 0 \text{ (Initial)} \\ 0, & \theta < 0,\ \dot{\theta} > 0 \text{ (Restore)} \\ d_r L_r, & \theta < 0,\ \dot{\theta} < 0 \text{ (Compress)} \end{cases}. \tag{5}$$

Under free vibration with the damping, *i.e.*, under a motion of the system (1) caused by nonzero initial conditions and a zero excitation and neglecting the friction torque, the equation of motion can be rewritten by

$$Ml^2\ddot{\theta} + D\dot{\theta} + (Mgl + K)\theta = 0. \tag{6}$$

Then the natural frequency $\omega_n$ and damping ratio $\zeta$ of the system can be solved as

$$\zeta = \frac{D}{\sqrt{KMl^2}},\ \omega_n = \sqrt{\frac{Mgl+K}{Ml^2}}.. \tag{7}$$

We can adjust the dynamic characteristics of the system with spring stiffness and damping coefficient value (we assume that the system total mass $M$, vertical height $l$ can not be easily changed).

To simplify dynamic response analysis, we set $L_f = L_r = L, k_{f1} = k_{f2} = k_{r1} = k_{r2} = k, d_f = d_r = d$ and assume $\theta$ is small (*i.e.*, operating position is near the initial position). The spring stiffness $K$ and damping coefficient $K$ become

$$K = \begin{cases} 3Lk, & \theta > 0 \\ 3Lk, & \theta < 0 \\ 2Lk, & \theta = 0 \end{cases},\ D = \begin{cases} Ld, & \theta > 0,\ \dot{\theta} > 0 \\ Ld, & \theta < 0,\ \dot{\theta} < 0 \\ 0, & \text{otherwise} \end{cases}. \tag{8}$$

In compressing motion ($|\theta|$ is increasing from zero), the spring stiffness is increased (from $2Lk$ to $3Lk$). The damping coefficient is also change to $Ld$ from zero. So the large spring and damping torques are generated against the falling pendulum motion (this is necessary for stable shock absorption). In restoring motion ($|\theta|$ is decreasing to zero), the spring stiffness is not changed, but damping torque becomes zero. This makes the pendulum easy to restore the initial pose (when $\theta = 0$, $K = 3Lk$ becomes smaller to $2Lk$, this is also helpful to reduce the magnitude of oscillation). In the moment of crossing the vertical line, the damping torque is generated to prevent large overshoot.

TABLE II

SPECIFICATIONS OF THE ROBOT

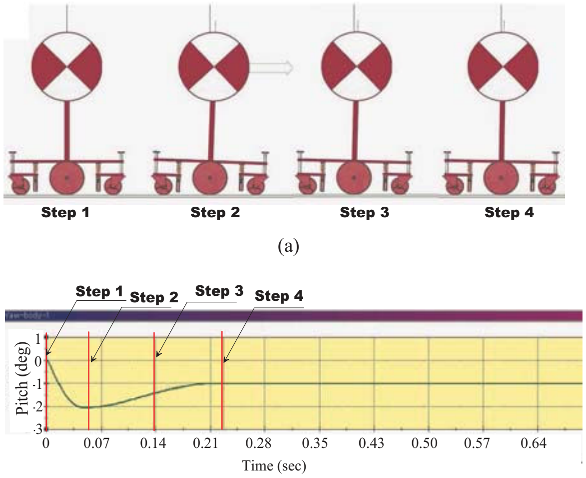
| Item | Content |
|---|---|
| Mass ($M$) | 60.00 $kg$ |
| Height of the center of mass | 0.55 $m$ |
| Horizontal distance between body center and front caster | 0.20 $m$ |
| Horizontal distance between body center and rear caster | 0.20 $m$ |
| Main spring constant of caster | 1200 $N/m$ |
| Damper return spring constant | 1000 $N/m$ |
| Damper coefficient of damper | 600 $Ns/m$ |
| Shaft friction | 10 $N$ |

We have achieved discrete-variable damping control with only passive spring-damper mechanism (this is achieved by novel spring-damper combination without any active control). The suggested multilayered suspension mechanism has also satisfied the conflicting design requirements: 1) large spring stiffness and zero damping force for the fast restoring to the initial posture, 2) sufficient damping force to minimize the oscillation of the system and 3) large spring and damping force for stable shock absorption.

## IV. SIMULATIONS

This section shows the simulations of a general spring-damper mechanism as shown in Fig 3 and the proposed *Multilayered Suspension mechanism* to demonstrate the usefulness and performance of the proposed mechanism. The motions of the mobile robot with each suspension mechanism have been simulated with the specifications of the mobile robot shown in Table II. Simulation conditions are defined as follows.

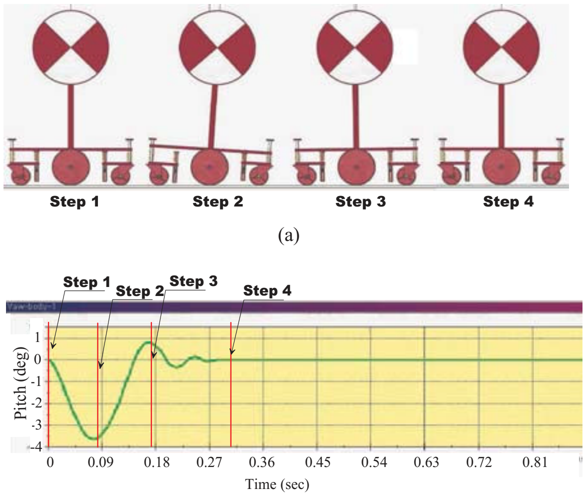
- Initially, as the mobile robot runs at the constant velocity and stops suddenly, the force by deceleration causes the inclination of the robot as $\theta$ is about 3°. At this time, the front suspension and the rear suspension of the robot are compressed and expended by the force, respectively.
- The horizontal distance $L_f$ between the body center and the front caster is equal to the distance $L_r$ between the body center and the rear caster. Actually, the distances $L_f$ and $L_r$ in the real robot are different from each other because the casters are rotated around the main shafts of the casters (which are mounted on the upper frames of robot as shown in Fig. 5) according to the robot motion. Although the difference of $L_f$ and $L_r$ has an effect on the recovering motion of the inclined robot, we did not consider this difference in order to compare only the features of the two suspension mechanisms.
- The effects of the nonlinearity and the coulomb friction in the dampers are based on the values designed and provided by the 3D simulation tool engine that is the COSMOSMotion of Solidworks because the effects cannot be easily calculated.



(a)

(b)

Fig. 9. Simulation results using spring-damp mechanism. (a) Simulator. (b) Pitch motion graph.



(a)

(b)

Fig. 10. Simulation results using *Multilayered Suspension Mechanism*. (a) Simulator. (b) Pitch motion graph.

Based on these conditions, Fig. 9 shows the simulation results using only spring-damp mechanism as shown in Fig 3. The robot tries to return to initial posture after the disturbance disappears but the robot does not return any more when $\theta = -1.2°$ because of the effect in the dampers. Fig. 10 shows the simulation results using *Multilayered Suspension* mechanism. The robot returns to initial position as shown in Fig. 10(b) after the disturbance disappears. The simulation results mean that *Multilayered Suspension Mechanism* is robust against disturbances such as sudden start, stop, and crash. The performance of the proposed mechanism can be different with respect to the change of mass, spring constants, and damping coefficients of the designed robot. The authors tried to optimize various parameters. The related study including the theoretical analysis of the mechanism will be presented in the full paper.

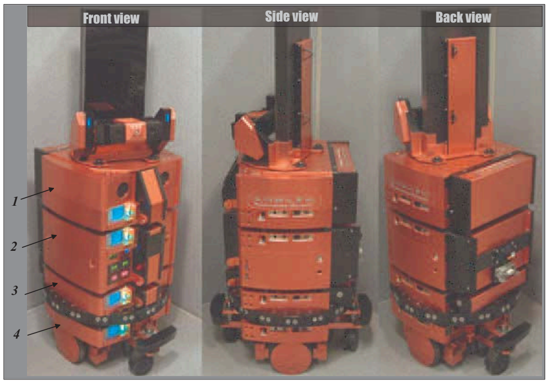


Fig. 11. Robot adopting proposed suspension mechanism. 1, 2, 3, and 4 represent a recognition, an arbiter, a sensor, and a mobile module, respectively.

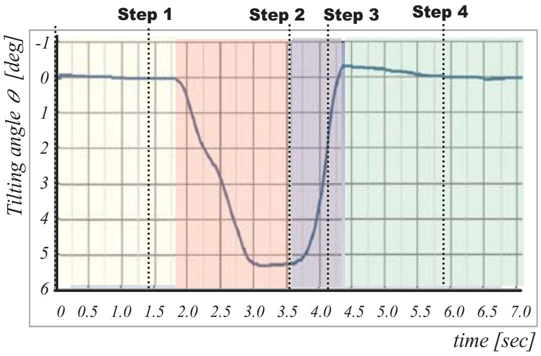


Fig. 13. Experimental result about restoring initial posture after tilting by moment.

## V. IMPLEMENTATION AND EXPERIMENTS

The proposed mechanism has been implemented in a mobile robot under development for an indoor environment, called a DRP I (*Dynamically Reconfigurable Personal robot I)* as illustrated in Fig. 11 [6]. Two experiments were conducted with this robot. Fig. 12 shows the response to the external force acting on the robot body in stop condition. Step 1 presents the robot's initial posture $\theta_i$ without an external disturbance ($\theta_i = 0$). In step 2, the robot is leaning at the maximum tilting angle $\theta_a$ by a downward force, when the user pushes down the rear of the robot. In step 3 when the user removes the force pushing the robot, the robot tries to return to the initial posture $\theta_i$ owing to the force by the springs in the mechanism. Step 4 shows that the robot has restored its initial posture. In this experiment, in order to measure the tilting angle of the robot, we use a sensing module which is composed of an one-axis gyro-sensor and an inclinometer; the resolution and the sensing frequency of this sensing module are $0.01°$ and $10Hz$, respectively.

Fig. 13 illustrates the changes in the robot's tilting angle from the steps 1 to 4. According to the graph, when the maximum tilting angle $\theta_a$ is $5.27°$, the maximum overshoot in percentage and the maximum overshoot angle are $100.3\%$ and $0.32°$, respectively. The rising time ($10\% \sim 90\%$) for restoring the initial posture is approximate $0.37sec$. The changing tendency of the tilting angle can be various depend-

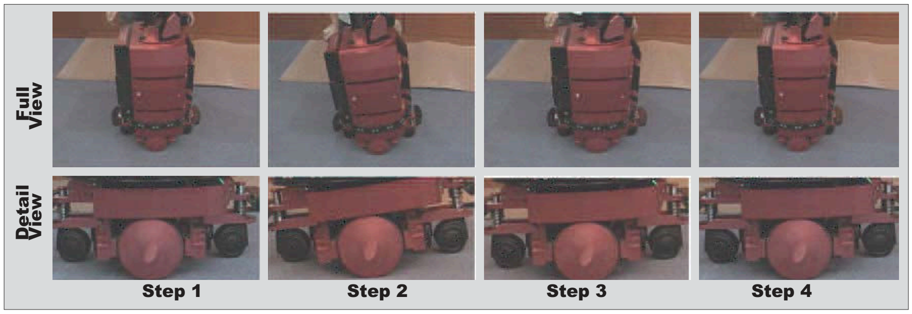


Fig. 12. Experiment on restoring initial posture after tilting by moment.

ing on the characteristics of springs and damper. However, regardless of these characteristics, the proposed mechanism is capable of maintaining the stable posture of a robot. This is because the mechanism was designed to remove unnecessary effects of the damper mechanically, as mentioned in Section III. Another experiment, which demonstrates the excellence of the *Multilayered Suspension Mechanism*, is shown in Fig. 14. When the robot moves on the uneven ground ($2cm$-high step), it keeps contact with the ground and smoothly overcome the unevenness. It necessarily follows that the robot restores its base posture after the cross movement.

The proposed mechanism surely provides a tall robot with a stable drive; this mechanism was adopted as a suspension mechanism of a commercial service robot in Korea through technology transfer. The proposed mechanism, however, leaves much room for improvement. For example, when the robot has arms, this mechanism as well as other suspension mechanisms can interrupt the manipulating operation of the robot because the suspension can act according to motions of the arms. In such a case, if the robot has an additional stopper to put a brake on the function of the suspension mechanism as occasion demands, the robot will be able to execute its task successfully.

## VI. CONCLUSIONS

In this paper, the author presented a novel design of the suspension mechanism for differential drive mobile robot to maintain stability and to obtain improved performances. The problems with the existing suspension mechanism have been discussed and to deal with the problems, a novel suspension mechanism has been proposed, where springs and dampers work differently according to the robot's inclined direction and angular velocity related to the pitch. Using this mechanism, the mobile robot had improved mobility as well as be protected from the shock of the uneven ground conditions. Moreover, the robot tilted by disturbances returned to the home position more accurately without the use of complicated control algorithms or additional actuators.

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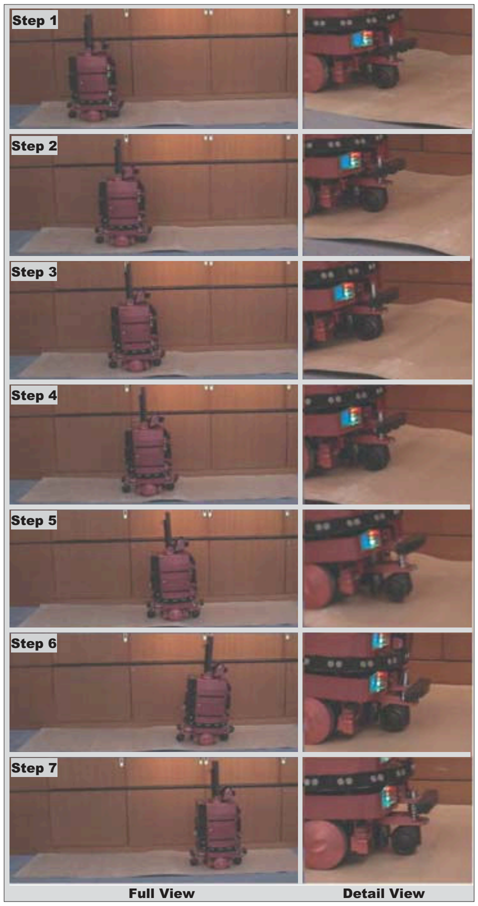

Fig. 14. Experiment on doorsill crossing.

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