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Development of a Four Wheeled Reconfigurable Mobile Robot and Effects of Driving Wheel Sideslips on Grassy Slopes

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Abstract

Wheeled mobile robots expect a high speed exploration and low production costs compared with crawler type of mobile robots. The four wheeled mobile robot has especially a simple driving mechanism and good maintenance characteristics. In the field of the farm machine, the four wheeled mobile robot on a rough terrain is expected as the farming autonomous robot. A four wheeled reconfigurable mobile robot is developed for use on the rough terrain slope. The developed mobile robot is composed of active articulated four legs and four driving wheels. The effectiveness of the developed mobile robot is shown in experimental results.

Keywords: Reconfigurable Robot, Rough Terrain, Sideslip, Grassy Slope

1. Introduction

In recent years, many rough terrain mobile robots have been developed for a target of autonomous exploration rovers such as lunar and space rovers [1, 2]. Furthermore, a field of a farm machine research is expected to develop farming autonomous robots on a rough terrain [3]. A farming autonomous robot is requested to move safely the rough terrain in a similar to the space rover. For example, an autonomous mower is easy to slip on a rough terrain such as grassy grounds. The development of the farming autonomous robot needs to consider the slip on the rough terrain. The rough terrain mobile robot has especially a sideslip influence by the Center of Gravity (CG) of itself in case the robot moves across rough terrain slopes. The sideslip influence gives a breakaway from a target path of the rough terrain mobile robot. The sideslip causes a rollover of the rough terrain mobile robot [4]. Therefore a driving mechanism avoiding the driving wheel sideslip is requested for the rough terrain mobile robot.

On the other side, many types of moving mechanisms for the rough terrain mobile robot have been developed as a means of rough terrain movements, for example legs, crawlers, wheels and these complex types. A wheeled mobile robot expects a high speed exploration and low production costs compared with a crawler type of mobile robot [5]. The four wheeled mobile robot has especially a simple driving mechanism and good maintenance characteristics. In the field of the farm machine research, the four wheeled mobile robot on the rough terrain is expected as the farming autonomous robot. However, the slip of the driving wheel becomes a problem on the rough terrain because of a small grounding area of the driving wheel. The sideslip on the driving wheel is especially the problem of the movement across the rough terrain slope in the case of the farming autonomous robot.

A four wheeled mobile robot is developed for use on the rough terrain slope. The rough terrain slope for an experimental environment is a case on grassy slopes, and has a driving wheel slip easily. The developed mobile robot is composed of active articulated four legs and four driving wheels. The active articulated leg adjusts the angle of bank and the height between the ground and the developed mobile robot body. The developed mobile robot with the adjustable mechanism is called "reconfigurable robots" [6]. An orientation of the developed mobile robot body is controlled by the rotational angle of the active articulated leg. The orientation control shifts the CG of the developed mobile robot. The shift of the robot CG is expected of the sideslip control on various rough terrain slope angles by using the developed mobile robot. Sideslip avoidance experiments by the developed mobile robot verify the effectiveness of the adjustable mechanism by the active articulated leg. The effectiveness of the developed mobile robot is shown in experimental results.

2. Four Wheeled Mobile Robot Development

The equable contact force of wheels leads into a static stability of a wheeled mobile robot. For example, the wheeled mobile robot is possible to avoid a trouble with a driving wheel sideslip on the rough terrain slope, if the wheel-terrain contact force equalizes with all wheels. The static stability of the wheeled mobile robot is also influenced by the shift of the CG by itself. The influence of the CG is studied in this section. And furthermore, the four wheeled mobile robot is developed in consideration with the shift of the CG.

2.1 A study of the shift of the CG in four wheeled mobile robot case

The design of a driving wheel mechanism is studied for the four wheeled mobile robot development. A clearance between the mobile robot body and the ground is problem to move the rough terrain. The front view of a four wheeled mobile robot without the clearance from the ground is shown in Fig. 1. The robot body of the four wheeled mobile robot collides the ground of the rough terrain by small clearance in Fig. 1. The four wheeled mobile robot cannot complete a goal if the worst comes to the worst. Therefore general rough terrain mobile robot, for example the space rover, is composed by an extension frame or passive suspension mechanism in shown Fig. 2. The clearance between the robot body and the ground is magnified by these. However, the robot CG becomes progressively higher by extending the frame.

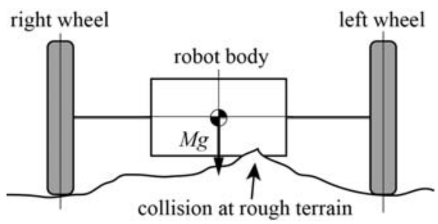

Fig. 1 The front view of the four wheeled mobile robot without the clearance from the ground

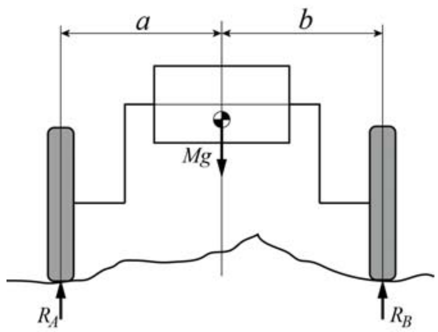

Fig. 2 The robot body lift up for a safe clearance

The position of the CG in the four wheeled mobile robot is $a = b$ on the level ground in Fig. 2. In Fig.2, M is the robot mass and g is the gravitational acceleration of Earth. The reaction forces of R_A and R_B from the ground are calculated by

$$R_A = R_B = \frac{Mg}{4} \tag{1}$$

In the case of Fig. 3, the reaction forces of R_A and R_B from the ground are calculated by

$$R_A = \frac{b}{a+b}\frac{Mg}{2} \tag{2}$$

$$R_B = \frac{a}{a+b}\frac{Mg}{2} \tag{3}$$

The reaction forces from the ground are $R_A > R_B$ in Fig. 3. Unequal contact force of wheels often causes the loss of ground contact on the rough terrain slope. The loss of ground contact has the driving wheel sideslip of the four wheeled mobile robot. The four wheeled mobile robot results in a rollover on the rough terrain slope if the worst comes to the worst. For example, it is thought that the farming autonomous robot has a manipulator on board. The position of the robot CG shifts higher by extended function of the farming autonomous robot. The shift of the CG from C to D gives more static instability of the four wheeled mobile robot in Fig. 3.

As a strategy for the equable contact force of right and left wheels in Fig. 4, the body height and the angle of bank of the four wheeled mobile robot are controlled by the right and left wheel heights. The robot body becomes on the level by a control strategy. The static stability by the equable contact force of wheels avoids the sideslip and rollover of the four wheeled mobile robot.

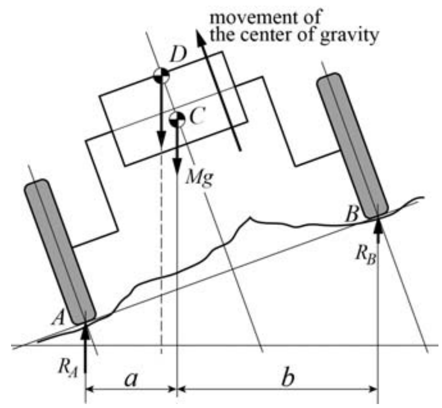

Fig. 3 Effect of the CG on the rough terrain slope

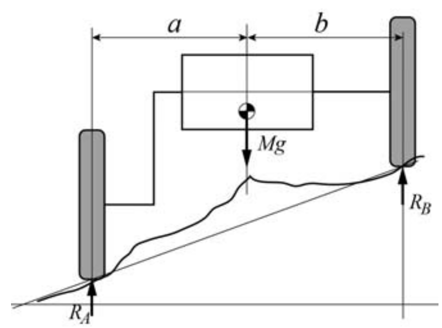

Fig. 4 Static stability of the reaction forces by a driving wheel transformation

2.2 Specifications of the developed mobile robot

A developed four wheeled reconfigurable mobile robot with active articulated four legs is shown in Fig. 5. Specifications of the developed mobile robot are the length of 545 mm, the width of 304 mm and the weight of 1.84 kg. The structure of the developed mobile robot is detailed in Fig. 6. Components the developed mobile robot include four driving wheels connected with geared motors, active articulated four legs connected with geared motors and the robot body. The geared motor is composed of a DC motor, a potentiometer, electrical parts and several gears (KRS-4034HV ICS: Kondo Kagaku Co., Ltd.). A pneumatic rubber tire is used for the driving wheel in consideration of a future farming autonomous robot use. Maximum and minimum heights of the developed mobile robot are shown in Fig. 7. The maximum height is 155 mm and the minimum height is 0 mm of the robot body bottom.

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Fig. 5 The developed four wheeled reconfigurable mobile robot

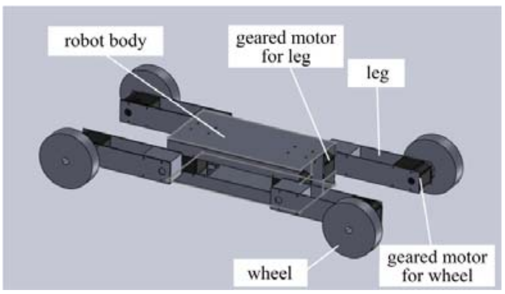
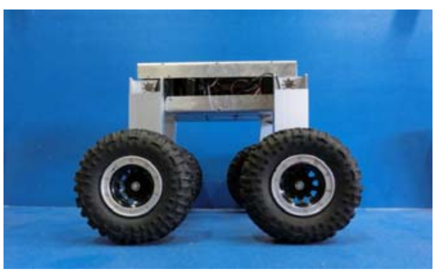
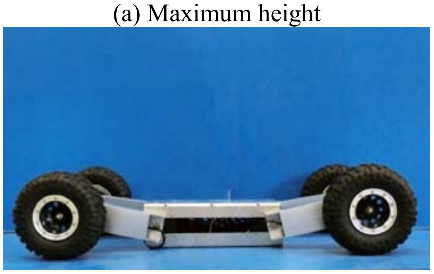


Fig. 6 Overall view of active articulated four legs and driving wheels with geared motors



(a) Maximum height



(b) Minimum height

Fig. 7 Lift up of the robot body bottom by active articulated four legs

The active articulated leg is independently controlled by a microcomputer (RCB-4HV: Kondo Kagaku Co., Ltd.) which is loaded in the robot body. The robot body height and the angle of bank of the developed mobile robot are controlled by the right and left active articulated legs. An acceleration sensor (RAS-2C: Kondo Kagaku Co., Ltd.) and battery are loaded in the robot body for autonomous robots. The acceleration sensor is used for the measurement of the angle of bank on the rough terrain.

3. Control Strategy of the CG

A schematic of the developed mobile robot is shown in Fig. 8. Notation including parameters of the developed mobile robot is as follows:

L_{max} : Maximum length (545 mm)
W_{max} : Maximum width (304 mm)
H_{max} : Maximum height of the bottom (155 mm)
l_B : Robot body length (200 mm)
w_B : Robot body width (105 mm)
h_B : Robot body height (60 mm)
w : Tread of driving wheels (250 mm)
l_S : Distance of leg rotational axes (175 mm)
l_{Leg} : Distance between axes of the leg and wheel (125 mm)
d : Diameter of the driving wheel (120 mm)
θ_i : Rotational angle of legs ($i = R, L$)
θ_{max} : Maximum leg rotational angle (90 deg.)
θ_{min} : Minimum leg rotational angle (-13.9 deg.)
h_i : Distance between the ground and the leg rotational axis ($i = R, L$)

Note, however, that h_R and h_L are changed by θ_R and θ_L of the active articulated legs.

3.1 Shift of the CG by control of the angle of bank

A schematic of the rough terrain slope is shown in Fig. 9 as an experimental environment. The developed mobile robot moves perpendicular to the rough terrain slope. This paper only considers the sideslip of the driving wheel by the shift of the CG. In a control strategy of the developed mobile robot, θ_R and θ_L are controlled with equal angles in front and back legs.

A front view of the schematic developed mobile robot is shown in Fig. 10. The robot body is the level by difference heights of right and left. The difference heights of right and left are given by h_R and h_L as the result of the active articulated leg rotation. The angle of bank η of the developed mobile robot equals the angle ϕ of inclination. The shift of the CG of the developed mobile robot is controlled by the change of η . A height difference Δh is $h_R - h_L$ in Fig. 10. In the control strategy of the developed mobile robot, the static stability by the equable contact force of the driving wheels is given by $\eta = \phi$. Pluses and minuses of η are defined in Fig. 11.The angle η is calculated by

$$\eta = \tan^{-1}\left(\frac{\Delta h}{w}\right)$$

$$\eta = \tan^{-1}\left(\frac{h_R - h_L}{w}\right)$$

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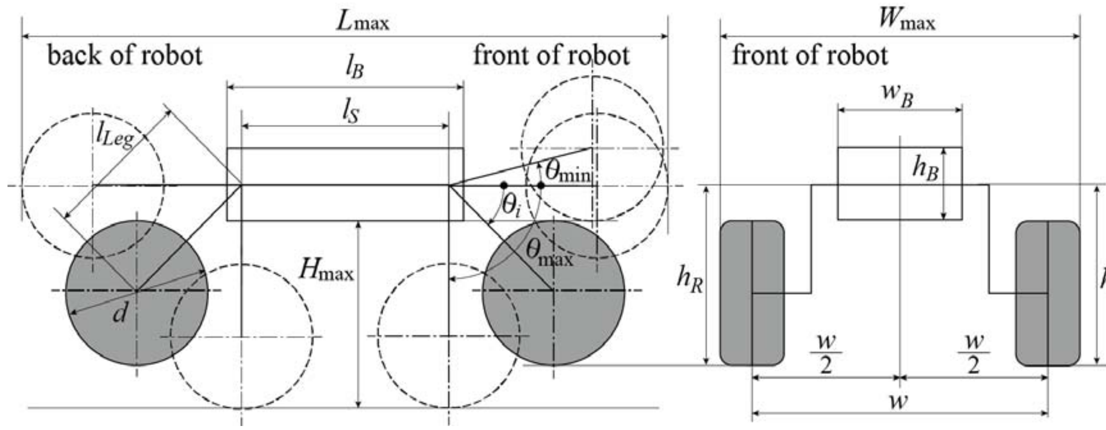

Fig. 8 Schematic of the developed mobile robot

$$\eta = \tan^{-1}\left(\frac{l_{Leg}\sin\theta_R - l_{Leg}\sin\theta_L}{w}\right) \quad (4)$$

where η is controlled by θ_R and θ_L of the active articulated four legs connected with the geared motors. Maximum η is 31.8 degrees calculated by $\theta_R = \theta_{max}$ and $\theta_L = \theta_{min}$ geometrically.

A change of the angle of bank $\Delta\eta$ results in a change of the angle of inclination on the slope in Fig. 12. Pluses and minuses of $\Delta\eta$ are defined in Fig. 13. In order to study the effect between the active articulated leg mechanism and driving wheel sideslip, the simple control strategy is use in this paper. The control strategy of the developed mobile robot gives the level of the robot body. The acceleration sensor on the robot body measures $\Delta\eta$, and η is calculated by θ_R and θ_L of the geared motors by Eq. (4). The modified angle of bank η_m for the level of the robot body is given by

$$\eta_m = \eta + \Delta\eta (= \phi) \quad (5)$$

where the developed mobile robot has controlled variables of θ_R and θ_L. The control strategy of the developed mobile robot chooses between the two variables. In the case of θ_R controlled by the geared motor, θ_R is calculated from Eq. (4) by a constant of θ_L. Therefore θ_R is calculated by

$$\theta_R = \sin^{-1}\left(\frac{w\tan\eta_m + l_{Leg}\sin\theta_L}{l_{Leg}}\right) \quad (6)$$

similarly θ_L is calculated by

$$\theta_L = \sin^{-1}\left(\frac{w\tan\eta_m - l_{Leg}\sin\theta_R}{l_{Leg}}\right) \quad (7)$$

In the case of $\eta > 0$, θ_R is modified, and in the case of $\eta < 0$, θ_L is modified as the control strategy of the developed mobile robot.

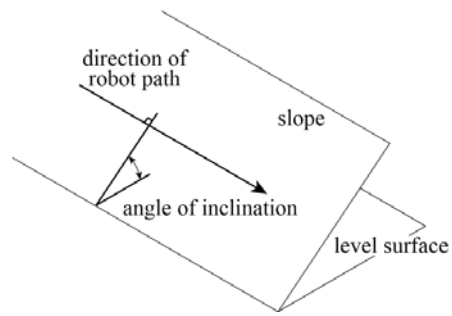

Fig. 9 Schematic of the rough terrain slope

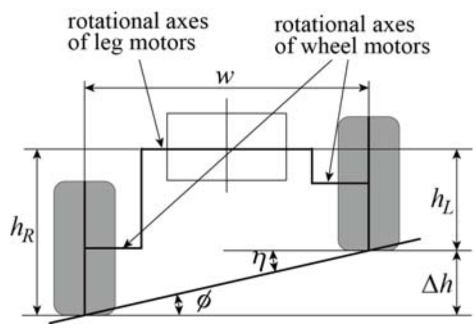

Fig. 10 The shift of the robot CG by the change of the angle of bank

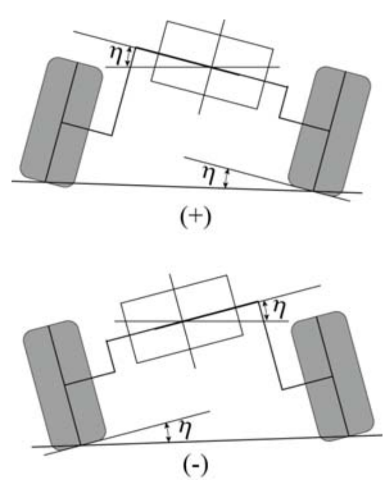

Fig. 11 The definition of the angle of bank

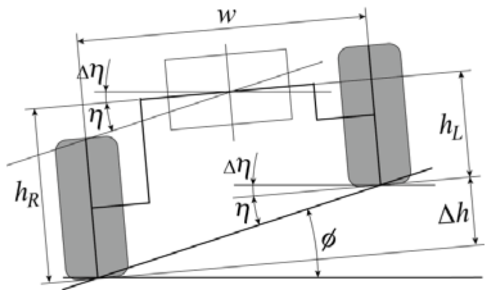

Fig. 12 Control strategy by the change of the angle of bank

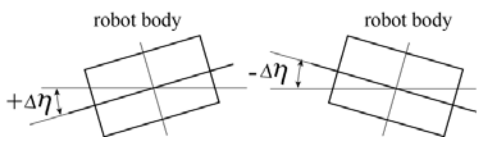

Fig. 13 The definition of the change of the angle of bank

3.2 Modification of driving wheel angular velocities

The rotation of the active articulated leg interferes in a driving wheel slip in Fig. 14. In Fig.14, contact points (P, Q) have the slip between the wheel surface and the ground. Where V is a desired robot velocity, $\dot{\theta}$ is an angular velocity of the active articulated leg, and $r(=d/2)$ is radius of the driving wheel. Angular velocities ω_F and ω_B of front and back driving wheels are modified by

$$\omega_F = \frac{V - l_{Leg}\dot{\theta}}{r} \quad (8)$$

$$\omega_B = \frac{V + l_{Leg}\dot{\theta}}{r} \quad (9)$$

The modified values of ω_F and ω_B are used for the velocity control of the developed mobile robot.

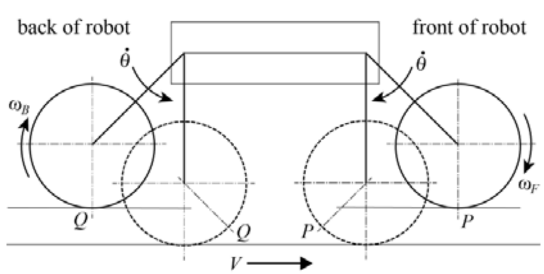

Fig. 14 Modification of driving wheel angular velocities

4. Experimental Results

4.1 Control of autonomous transformation

Experimental result of an autonomous transformation control is shown in Fig. 15. The developed mobile robot moves on a flat board (2.0 m× 1.0 m) by the autonomous transformation control. The flat board angle of inclination is changed while the robot movement. The developed mobile robot performance is verified by the tracking control of the angle of inclination. The level of the robot body is given by the transformation of the legs and driving wheels while the robot movement. The effectiveness of the autonomous transformation control is shown in Fig. 15. The developed mobile robot can moves without the driving wheel sideslip in the case of the change of the angle of bank by the autonomous transformation control.

However, in the case that θ_R and θ_L are fixed angular 0 degrees, the developed mobile robot has an unallowable sideslip of the driving wheel. The robot movement is unfinished on the flat board slope.

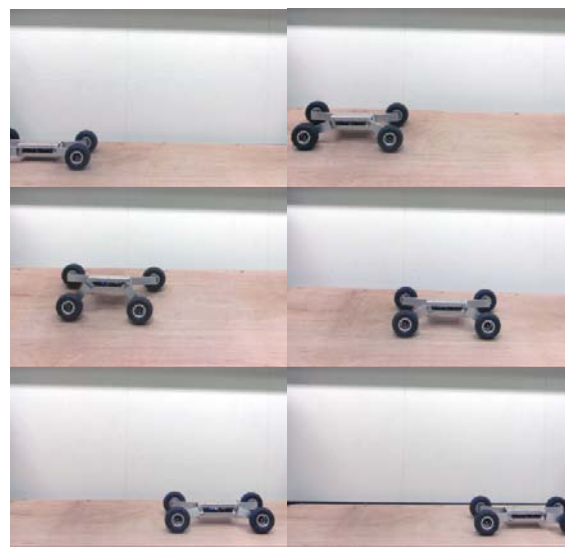

Fig. 15 Autonomous transformation by the change of the angle of inclination on the slope

4.2 Experiments on grassy rough terrain slopes

Experiments of outdoor environments need various rough terrain slopes. The angles of inclination on the slopes are available at 25 degrees, 31 degrees, and 36 degrees as the experimental environment. These outdoor environments have a grassy rough terrain. The developed mobile robot is controlled by conditions that controls of active articulated leg angle are fixed angular 90 degrees, fixed angular 0 degrees, and autonomous transformation control, for the leg rotational angles of θ_R and θ_L . Experimental conditions and detailed results are shown in Table. 1. Experimental results at the 31 degrees angle of inclination on the grassy slope are also shown in Figs. 16 - 18.

In the case of fixed angular 90 degrees at θ_R and θ_L, the developed mobile robot has a sideslip on all the grassy rough terrain slopes of the experimental environment. In Fig. 16, the developed mobile robot results in an unallowable sideslip on the 31 degrees angle of inclination. And furthermore, the developed mobile robot results in the unsafe rollover on the 36 degrees angle of inclination. In the case of fixed

Fig. 16 An unallowable sideslip of the robot in the case of θ_R and θ_L = 90 degrees

Fig. 17 An allowable sideslip of the robot in the case of θ_R and θ_L = 0 degrees

Fig. 18 Autonomous transformation control of the angle of bank by the active articulated leg and sensor

Table. 1 Experimental results

Robot Conditions	Slope angle of inclination		
	25 deg.	31 deg.	36 deg.
90 deg.	allowable sideslip	Unallowable sideslip	Rollover
0 deg.	good	Allowable sideslip	Unallowable sideslip
Automatic	good	good	Allowable sideslip

angular 0 degrees at θ_R and θ_L, the developed mobile robot has an allowable sideslip on the 31 degrees angle of inclination in Fig. 17. The 36 degrees angle of inclination on the grassy slope has an unallowable sideslip at the mobile robot driving wheel.

In Fig. 18, however, shift of the CG by autonomous transformation results in the stable movement by the proposed control strategy at the 31 degrees angle of inclination. The shift of the robot CG is automatically controlled by the active articulated leg and acceleration sensor. The robot body orientation is control in the level automatically. The equable contact force of wheels leads into the stable movement. The developed mobile robot results in an allowable sideslip on the 36 degrees angle of inclination. The effectiveness of the developed reconfigurable mobile robot and proposed control strategy are shown in the experimental results.

As compared with other four wheeled mobile robots, the developed mobile robot has especially the useful result on the rough terrain slope by the mechanism of the body height control. However, the developed mobile robot involves getting over obstacles on the rough terrain in future. The crossing obstacle on the rough terrain is a problem to be solved in the developed mobile robot.

5. Conclusions

The four wheeled reconfigurable mobile robot has been developed for use on the rough terrain slope. The developed mobile robot is composed of active articulated four legs and four driving wheels. The orientation of the robot body is controlled by the active articulated leg. The sideslip avoidance experiment by the developed mobile robot is verified the effectiveness of the adjustable mechanism by the active articulated leg. The effectiveness of the developed mobile robot is shown in the experimental result.

In future work, an optimum angular control algorithm of the active articulated leg and dynamic analysis of driving wheel friction on the rough terrain slope are problems to be solved in the developed mobile robot. And furthermore, the developed mobile robot involves getting over obstacles on the rough terrain.

6. References

[1] R. Volpe, Baumgartner, E. Schenker, P. and Hayati, S. (2000). Technology Development and Testing for Enhanced Mars Rover Sample Return Operations, paper presented in *IEEE Aerospace Conference*, Big Sky, Montana, USA

[2] Norouzi, M. Valls Miro, J. and Dissanayake, G. (2016). Probabilistic stable motion planning with stability uncertainty for articulated vehicles on challenging terrains, *Applied Autonomous Robots*, vol.40 (2), February 2016, pp.361–381.

[3] Daltorio, K. A. Rolin, A. D. Beno, J. A. Hughes, B. E. Schepelmann, A. Green, J. Branicky, M. S. and Quinn, R. D. (2010). An Obstacle-Edging Reflex for an Autonomous Lawnmower, paper presented in *Proceedings of the 2010 IEEE/ION Position Location and Navigation Symposium (2010 ION/IEEE PLANS)*, Indian Wells, CA, USA.

[4] Peters, S. C. and Iagnemma, K. (2006). An Analysis of Rollover Stability Measurement for High-Speed Mobile Robots, paper presented in *the 2006 IEEE International Conference on Robotics and Automation*, Florida, USA.

[5] Nakajima, S. (2009). Concept of a Novel Four-wheel-type Mobile Robot for Rough Terrain, RT-Mover, paper presented in *the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, St. Louis, USA.

[6] Iagnemma, K. Rzepniewski, A. Dubowsky, S. and Schenker, P. (2003). Control of Robotic Vehicles with Actively Articulated Suspensions in Rough Terrain, *Applied Autonomous Robots*, vol.14 (1), January 2003, pp.5–16.