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Rough Terrain Locomotion of a Leg-Wheel Hybrid Quadruped Robot

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***Abstract* – This paper proposes a new mechanism and control method of 4-leg-wheel hybrid locomotion. Many previous hybrid vehicles execute wheel-mode and leg-mode alternatively. However, to overcome higher obstacle with sufficient velocity, a wheel locomotion should continuously be executed. In this paper, suitable load distribution control is proposed considering a contact force to the ground and step edge, a wheel driving torque, and a friction coefficient of the wheel and terrain. In a proposed new leg-wheel hybrid mechanism, load distribution control is realized by a torque of twisting joint at the center of the body, and a forward/backward shift of the body. The validity of this control and mechanism is confirmed by some experiments, where vehicle can run over a 105mm step by 90mm radius wheels with a good continuous movement. With an adjustment control of the approach angle, a robot can also ride over a 230mm step.**

Index Terms – Leg-Wheel, Quadruped, Robot, Rough Terrain.

I. INTRODUCTION

In various fields, excellent locomotive mechanisms are required. Therefore, various locomotive mechanisms are proposed and researched now [1]. The purpose of this research is also to develop a locomotive mechanism that has an excellent locomotive ability.

A. Typical Locomotive Mechanisms

There are three typical locomotive mechanisms, "Wheel mechanism", "Crawler mechanism", and "Leg mechanism". From the viewpoints of "Locomotive efficiency" and "Mechanism complexity", wheel mechanism is the most excellent one. On the other hand, from the viewpoints of "Rough terrain locomotion ability", leg mechanism is the most excellent one.

B. Leg-Wheel Mechanism

Focusing attention on wheel mechanism and leg mechanism, it seems to be possible by combining these two mechanisms well, to produce "Leg-wheel mechanism" which is excellent in both points of locomotive efficiency and rough terrain locomotion ability. However, if these two are combined simply, leg-wheel mechanism becomes worse than leg mechanism in the point of mechanism complexity [2]. So it is necessary to devise the degrees of freedom arrangement.

On the other hand, some kind of leg-wheel mechanism rocomotes uses its wheels only on flat terrain, and doesn't use its wheels on rough terrain [3]. In order to bring out locomotive efficiency even on rough terrain, the locomotion must be based on wheels. Therefore, the purpose of this research is proposing a new leg-wheel mechanism that satisfies these requirements, formulating the control method for this mechanism to locomote efficiently and automatically, and confirming them experimentally with a real machine.

II. ROUGH TERRAIN LOCOMOTION WITH WHEEL MECHANISM

A. Necessary Conditions for Rough Terrain Locomotion

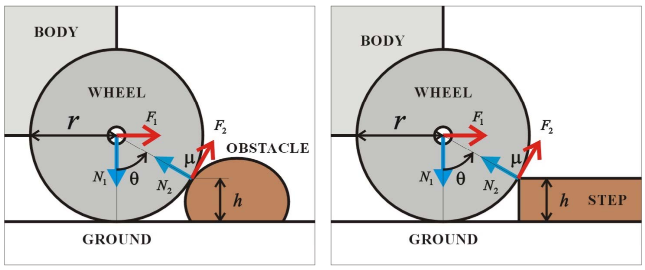
Whether wheel mechanism can move or not depends on the radius and the maximum output of wheels, and the static friction condition between wheels and ground. The former can be controlled by designing the mechanism well. But the latter depends on a state of the ground, so it's more difficult to control. Therefore, we focus attention on it.

B. Definition of Rough Terrain for Wheel Mechanism

When wheel mechanism moves, there is an instantaneous center. So the wheel contacts with the ground at this point. Therefore, we should consider static friction condition at this contact point. Moreover, from the viewpoint of this condition, two situations shown in Fig.II-I are same. So the rough terrain for wheel mechanism can be defined as the terrain that is build up with arbitrary steps. At the following, we consider step-climbing of wheel mechanism.

C. Formulation of Static Friction Condition

Now we consider necessary conditions for step-climbing of wheel mechanism with Fig.II-I (ii). In this figure, r means the radius of the wheel, μ means the coefficient of static friction, F_1 means the horizontal component of force the wheel receives from the body, N_1 means the load which the wheel receives, F_2 means the frictional force and N_2 means the normal force which occur between the wheel and the step, and



(i) Arbitrary Shape Obstacle (ii) Step

Fig. II-I Contact Point between Wheel and Rough Terrain the range of θ is $(0 < \theta \leqq 90°)$. Considering two force balance conditions and a static friction condition about the wheel, the following relation is derived. However, ε in the equation means F_1/N_1 .

$$\theta < \cot^{-1}\{(1-\mu\varepsilon)/(\mu+\varepsilon)\} \qquad \text{(II-I)}$$

Therefore, μ, ε decide the maximum θ and h of the step which the wheel can start to climb up. And when $\mu\varepsilon > 1$, θ can be 90 degrees and the wheel can start to climb up the step which is taller than r . In this case, maximum h doesn't depend on r .

D. *Step-climbing of General Wheel Mechanism*

To derive step-climbing conditions of a general four-wheel driving vehicle, now we consider a situation shown in Fig.II-II. In Fig.II-II (ii), $4M$ means the weight of the whole vehicle. Considering two force balance conditions, F_{1x} is equal to the summation of F_{2x}, F_{3x}, F_{4x} , and assuming that there is no force between wheels in y direction, $F_{1y}, F_{2y}, F_{3y}, F_{4y}$ are same value F_y . So considering static friction condition, maximum of F_{2x}, F_{3x}, F_{4x} are same value F_x . Therefore, considering a moment balance condition, the following relation is derived. However, wheels are much smaller than the body.

$$WF_x = LF_y \qquad \text{(II-II)}$$

Moreover, the following relation is derived from the static friction condition.

$$F_{1x} = 3F_x = \left(3\mu \big/ \sqrt{1 + W^2/L^2}\right) \cdot M \qquad \text{(II-III)}$$

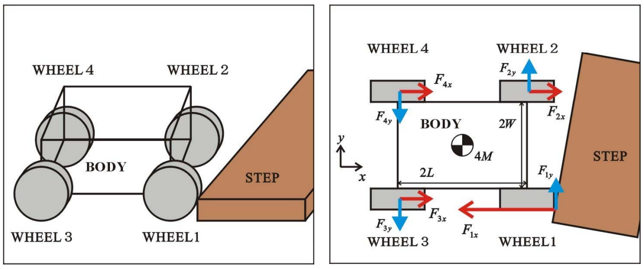
On the other hand, when F_1 which is the resultant force of F_{1x} and F_{1y} becomes completely normal to the step, the static friction condition for step-climbing becomes the best. In this case, F_1 becomes as follows, and the entry angle of the wheel to the step is $\tan^{-1}(W/3L)$.

$$F_1 = \mu\sqrt{(9L^2 + W^2)/(L^2 + W^2)} \cdot M \qquad \text{(II-IV)}$$

In the case of eq.(II-V), the load WHEEL1 receives is M . So ε in eq.(II-I) becomes $\mu\sqrt{(9L^2 + W^2)/(L^2 + W^2)}$, and a friction condition to starts to climb up the step $(h \geqq r)$ becomes as follows.

$$\mu > \sqrt[4]{(L^2 + W^2)/(9L^2 + W^2)} \qquad \text{(II-V)}$$

Substituting 1/2 for W/L , μ should be more than 0.61. And this value comes from the theory under ideal conditions. So in fact, the less slippery environment is required. This is the limit of step-climbing ability of a general four-wheel driving vehicle. Moreover, if the movable range of its suspension is not wide enough, the more it climbs up the step, the larger the load distribution of the wheel becomes. In the case of the step-climbing of WHEEL3, 4, we can use eq.(II-I), too. But the load distribution changes and step-climbing becomes more difficult, because the whole of the vehicle inclines and the loads of rear wheels become heavier than front wheels.



(i) Assumed Situation (ii) Horizontal Forces for Vehicle

Fig. II-II Step-Climbing of Four-Wheel Driving Vehicle

III. CHARACTERISTICS OF LEG MECHANISM

Leg mechanism is a mechanism that can change the relative position of its feet based on its center of gravity (COG). So it can lift and move its foot, therefore it can walk. At the following, we think about mechanisms, which have more then four legs to be able to walk statically.

These mechanisms can select which foot they will lift, and it means they can control "Load distribution of feet" with its feet grounded. This distribution is decided by the horizontal relative position of the feet and the COG, and statically indeterminate conditions. The former can be controlled by effects of moving the COG in the horizontal. So these effects can give two degrees of freedom at a maximum to this distribution.

On the other hand, the latter can be controlled by effects of moving feet in the vertical. And the number of statically indeterminate conditions is equal to "(Number of legs) - 3". So these effects can give this number of degrees of freedom at a maximum to the load distribution. So the total number of degrees of freedom which this distribution has is "(Number of legs) - 1" at a maximum. This "- 1" comes from constraint condition of the total weight of mechanism.

Therefore, in the case of four legs mechanism, the load distribution of feet can have three degrees of freedom. So three active joints (one is for a statically indeterminate condition) are needed to control it.

IV. PROPOSED LEG-WHEEL MECHANISM

A. *Necessary Conditions of Proposed Mechanism*

1) Wheel : To realize the mechanism that has both advantages of wheel and leg mechanisms on the rough terrain, we select a mechanism that combined serially. So we propose the mechanism that has active wheels on the feet.

2) Number of Legs : To reduce mechanism complexity, we should reduce the number of legs as much as possible, and the mechanism can walk. So we select four legs mechanism.

3) Movement of COG : We propose a mechanism based on wheel mechanism. So it doesn't move omnidirectionaly. Therefore, we consider that only one active joint is enough for the movement of the COG.

4) Statically Indeterminate Condition : As explained in chapter III, to control a statically indeterminate condition of four legs mechanism, only one active joint is needed. And the movable range of this joint should be wide enough to respond to the rough terrain.

5) changing Leg Attitude : As one of the necessary condition to be able to walk, another joints are required, which can move foot in the horizontal.

B. Explanation of Proposed Mechanism

1) Degrees of Freedom Arrangement: The proposed mechanism is as shown in Fig. IV-I. It has two active slide joints between the body system and leg system, which can move the leg system to the body system. And it has one twist joint that can twist the body system. Moreover, it has two passive joints between the body system and the leg system.

2) Slide Joints : These joints can move the position of COG without changing the positions of wheels. So as shown in Fig.IV-II, on the terrain where the mechanism inclines, they can resolve the bias of "Load distribution of wheels" which comes from the bias of the COG.

3) Twist Joint : This joint can control a statically indeterminate condition. And the movable range of it is so wide, as shown in Fig.IV-III, it can ground four wheels on the ragged terrain. Moreover, the state of no torque, which needs no energy, makes the loads of left and right wheels equal.

4) Passive Joints : With these two passive joints and two slide joints, this mechanism can generate static walking [4]. And as shown in Fig.IV-IV, the attitude of these joints is controlled by the speed difference of left and right wheels without hanging up legs. However, these joints need a lock mechanism. The reason for it is explained in chapter V.

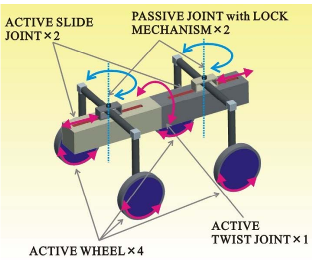


Fig. IV-I DOF Arrangement

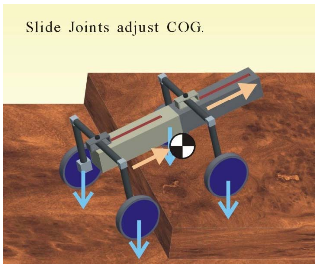


Fig. IV-II Effect of Slide Joints

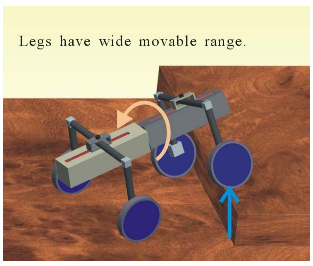


Fig. IV-III Effect of Twist Joint

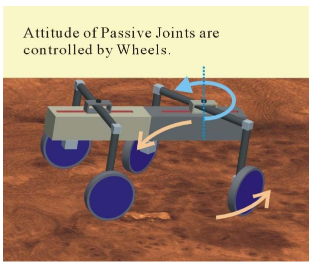


Fig. IV-IV Passive Joints

V. Rough Terrain Locomotion of Proposed Mechanism

A. Basic Principle for Step-Climbing of Leg-Wheel

The basic locomotion of the proposed mechanism is the locomotion with four wheels even on the rough terrain. So we can use the theory explained in chapter II, and we can verify Rough terrain locomotion ability with eq.(II-I). In the case of four-wheel driving vehicle, it cannot control Load distribution of wheels. But the proposed mechanism can control it, so the mechanism can get much better ability for step-climbing. There are three important elements as shown in Fig.V-I.

1) Pushing Force : The front right wheel is pushed to the step by thrust forces generated by other wheels.

2) Load Reduction : To drive the twist joint, the load of the front right wheel can be reduced dramatically. So ε in eq.(II-I) can be increased dramatically, too. Therefore, this mechanism can satisfy the static friction condition and locomote on a slippery environment.

3) Trust Force : The front right wheel drives itself and generates the thrust force.

This principle is adaptable to the step-climbing of other wheels. But before the load reduction, the bias of the load distribution of wheels should be resolved. If the bias exists, before the load of the wheel that contacts with the step is reduced enough, that of the other wheel reaches zero. In this case, the mechanism cannot climb up the step.

B. COG Position Compensation by Slide Joints

The slide joints can compensate the COG position. These Joints have the movable range, so there is a limit of the compensation. Moreover, the relation between the amount of the distance of the joints and that of COG position is decided by the mass ratio between the body system and the whole mechanism. If this ratio is large, the limit of compensation becomes better. On the other hand, the COG height becomes higher, so more distance of the compensation is needed. Now

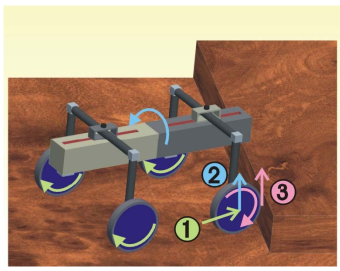
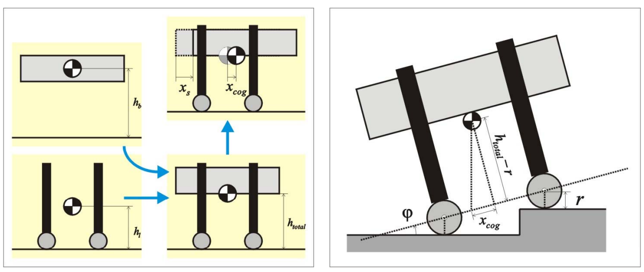


Fig. V-I Basic Principle for Step-Climbing



(i) Body and Leg-Wheel System (ii) COG Bias

Fig. V-II COG Position Compensation by Slide Joints we consider this mass ratio from the viewpoint of the COG position compensation.

At first, as shown in Fig.V-II (i), we consider the situation that the mechanism stands on the horizontal plane. In this figure, h_b means the COG height of the body system, h_l means the COG height of the leg-wheel system, h_{total} means the COG height of the whole mechanism, x_s means the distance of the slide joints, x_{cog} means the distance of the whole mechanism COG, m_b means the mass ratio. These values have the relation as follows. However, if m_b changes, each COG height doesn't change.

$$h_{total} = m_b h_b + (1 - m_b) h_l \tag{V-I}$$

$$x_{cog} = m_b x_s \tag{V-II}$$

Next, we consider the situation that the mechanism inclines when it is climbing up a step. While the step-climbing, as shown in Fig.V-II (ii), the mechanism incline the most in the situation that two wheels are on the step. So we consider this situation. In this figure, to compensate the load distribution of wheels completely, the distance that the COG should be moved is x_{cog} . In this case, the necessary distance of the slide joints (x_s) is as follows.

$$x_s = \{(h_b - h_l) + (h_l - r)/m_b\} \cdot \tan\varphi \tag{V-III}$$

Generically, the COG height of the leg-wheel system is higher than the radius of the wheel ($h_l > r$). Therefore, if m_b becomes larger, x_s becomes smaller. So the leg-wheel system had better become as light as possible, and the body system had better become as heavy as possible. However, if the total weight increases, the necessary output of actuators and the rolling resistance of wheels also increase. So we should decide the weight of the body system with considering these conditions.

C. *Effect of Leg Attitude*

The proposed mechanism can control passive joint angles by the speed difference of wheels. To analyze the effect of the leg attitude, we consider the situation as shown in Fig.V-III. In this figure, $N_{fr}, N_{fl}, N_{rr}, N_{rl}$ mean the loads of each wheel and $4M$ means the summation of them, T_t means the torque of the twist joint, θ_f, θ_r means the joint angles of the passive joints. Considering the positional relation between the COG and the centers of wheels, and the moment balance around J_t , the following relation about is $N_{fr}, N_{fl}, N_{rr}, N_{rl}$ derived. However, when T_t is increased, N_{fr} is decrease.

$$G(\theta_1, \theta_2) = (W/2L)(\tan\theta_1 - \tan\theta_2) - 1/\cos\theta_1 \tag{V-IV}$$

$$\begin{pmatrix} N_{fr} \\ N_{fl} \\ N_{rr} \\ N_{rl} \end{pmatrix} = \begin{pmatrix} 1 & G(\theta_f, \theta_r) \\ 1 & -G(-\theta_f, -\theta_r) \\ 1 & -G(-\theta_r, -\theta_f) \\ 1 & G(\theta_r, \theta_f) \end{pmatrix} \begin{pmatrix} M \\ \\ \dfrac{T_t}{2W} \end{pmatrix} = M_a \begin{pmatrix} M \\ \\ \dfrac{T_t}{2W} \end{pmatrix} \tag{V-V}$$

The second row in the matrix M_a in eq.(V-V) means the effect of the leg attitude for the load distribution of the wheels. For example, as shown in Fig.V-IV, in the case of ($\theta_f = -45°, \theta_r = 0°, W/L = 1$), M_a is calculated as follows.

$$M_a = \begin{pmatrix} 1 & 1 & 1 & 1 \\ -1.91 & 0.91 & 1.5 & -1.5 \end{pmatrix}^T \tag{V-VI}$$

In the second row in this matrix, we can recognize the third element is about 1.6 times larger than the second element. So it is easier to reduce the load of WHEEL3 than WHEEL2. Therefore, when the mechanism inclines on the rough terrain, if this effect is used with the effect of the slide joints, we can get better Locomotion ability.

D. *Necessity of Loch Mechanism*

The reasons why the passive joints are needed are as above. But if these joints are completely passive, as shown in Fig.V-VI, the state of the forces when one of the wheel contacts with the step becomes. So the pushing force that WHEEL1 receives becomes much smaller than in the case of Fig. II-II. Moreover, considering moment balances of leg-wheel systems, the values of $F_{1x}, F_{2x}, F_{3x}, F_{4x}$ must be same. Therefore, if the load of WHEEL1 is reduced, that of WHEEL4 is also reduced and all of $F_{1x}, F_{2x}, F_{3x}, F_{4x}$ are reduced. So ε in eq.(II-I) cannot be increased. This means that the effect of passive joints eliminates the effect of the twist joint. Therefore, the passive joints need a lock mechanism.

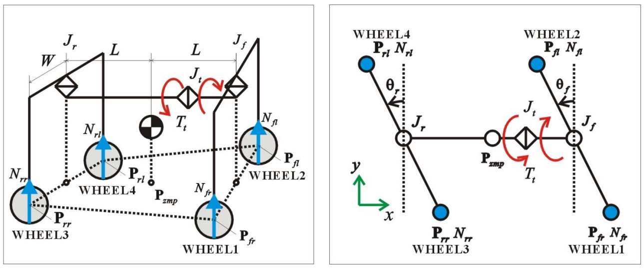


Fig. V-III Change of Twist Joint Effect by Change of Leg Attitude

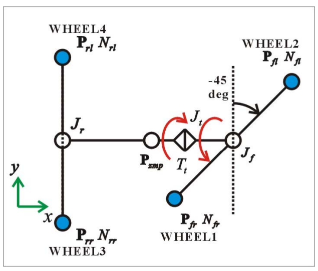


Fig. V-IV Example of Leg Attitude

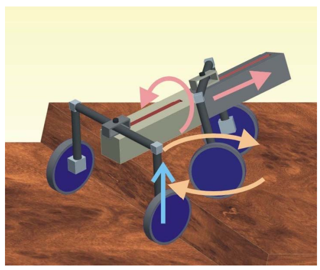


Fig. V-V High Step-Climbing

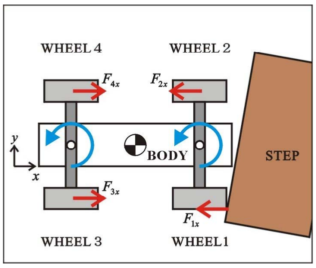


Fig. V-VI Bad Effect of Passive Joints

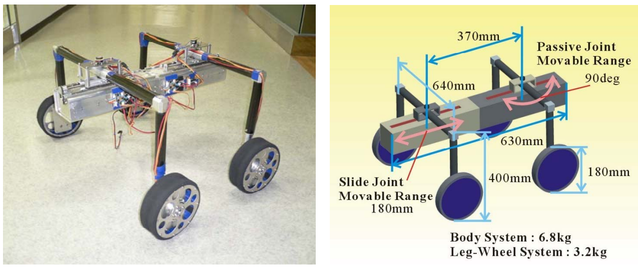


Fig. VI-I Real Machine

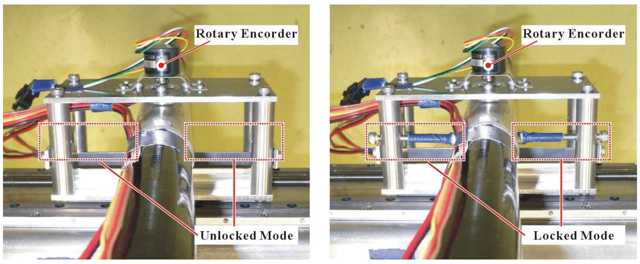


Fig. VI-II Passive Joint of Real Machine

VI. REAL MACHINE OF PROPOSED MECHANISM

A. Explanation of Real Machine

We made the real machine as shown in Fig.VI-I (i). Its dimensions and mass are as shown in Fig.VI-I (ii). Actuators are all electronic motors that have 20W rated output each, so the condition of output is enough. The passive joint is as shown in Fig.VI-II, it has a rotary encoder to recognize the joint angle, and the lock mechanism is simple one.

B. Basic Leg-Wheel Locomotion Method for Real Machine

Now we propose the basic method of the leg-wheel locomotion on rough terrain for the real machine. This is based on that of Wheel mechanism, and added the property of Leg mechanism. We explain how to control the joints and wheels.

1) Slide Joints : In this method, we drive both two joints equally by that one subordinates another one. We apply the position control to these joints. When the machine inclines on the rough terrain, we compensate the bias of COG position with driving these joints.

2) Twist Joint : We apply the torque control to this joint. Normally the torque is zero, and when it is recognized that one of wheels contacts with the step, the torque is generated in the direction to reduce the load of that wheel. However, the maximum torque is decided under the condition that all loads of wheels don't reach zero.

3) Passive Joints (and Wheels) : We normally set both of these joints in a locked state. The lock state has a play about 1 degree, so this state still has a very small movable range. Then, we apply the speed control to the wheels and control the joint angels of passive joints. In this control, command angles are the center of the movable ranges. While in rough terrain locomotion, if one of the wheels contacts with some obstacle, it becomes impossible to control the joint angle and the joint reaches the movable range limit. So with this property, the machine can recognize an obstacle. And considering following three conditions, which direction the machine locomotion is, which passive joint reaches the limit, which side of the limit the joint reaches, it is possible to judge which wheel contacts with the obstacle.

And to get the state as shown in Fig.II-II (ii), directions of all trust forces generate by wheels must be same as the direction of the machine locomotion. To satisfy this condition, the control method shown in the following equation is proposed. However, as shown in Fig.VI-III, $\theta_{f,cmd}, \theta_{r,cmd}$ mean the command angles, θ_f, θ_r mean the joint angel, θ_{lmt} means the movable range, V_{cmd} means the command velocity for the machine and $0 < \alpha < 1$.

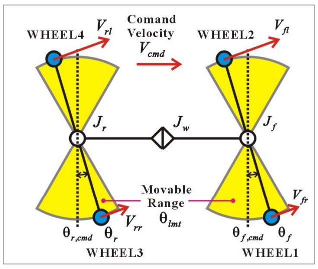


Fig. VI-III Control of Joint Angles

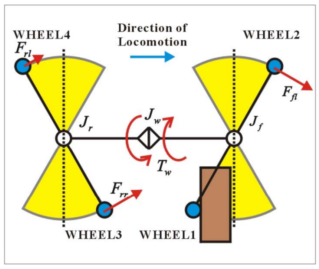


Fig. VI-IV Obstacle Climbing State

$$\begin{pmatrix} V_{fr} \\ V_{fl} \\ V_{rr} \\ V_{rl} \end{pmatrix} = \begin{pmatrix} 1 & 2(\theta_{f,cmd} - \theta_f)/\theta_{lmt} \\ 1 & -2(\theta_{f,cmd} - \theta_f)/\theta_{lmt} \\ 1 & 2(\theta_{r,cmd} - \theta_r)/\theta_{lmt} \\ 1 & -2(\theta_{r,cmd} - \theta_r)/\theta_{lmt} \end{pmatrix} \begin{pmatrix} V_{cmd} \\ \alpha |V_{cmd}| \end{pmatrix} \quad \text{(VI-I)}$$

All of elements in the matrix in eq.(VI-I) are always between –1 and 1, so it can satisfy the condition about thrust forces under arbitrary V_{cmd}.

And as explained in chapter V, when the machine climbs up an obstacle, both passive joints must reach the movable range limit. So when one of the joint reaches the limit, we stop the control of the joint angle of another joint. And as shown in Fig.VI-III, another joint also reaches the limit because the wheel which is reduced its load by the twist joint becomes slippery. In this state, we observe and control the joint angle of the side of climbing up an obstacle. And when the climbing up is finished and the joint angle control becomes possible, we restart to control another joint angle.

VII. STEP CLIMBING EXPERIMENT WITH REAL MACHINE

A. *Confirmation of Basic Method of Leg-Wheel Locomotion*

1) Conditions : In this experiment, we confirmed the availability of the proposed basic method of Leg-wheel locomotion. The experiment scenery is as shown in Fig.VII-I. In the experiment, the coefficient of the static friction was about 0.5, the height of the step was 105mm(higher than the radius of wheels). Therefore, as explained in chapter II, the four-wheel driving vehicle cannot climb up the step. And in order to determine the effects of the machine velocity and the incident angle to the step, we conducted the experiment under several conditions, the velocities are 31mm/s, 250mm/s, 500mm/s and the angle is between 0 and 90degrees.

In the experiment, the twist joint torque and the passive joint angles were controlled automatically. In this experiment, α in eq.(VI-I), the parameter to control the passive joint angles was 0.25. And beforehand the maximum twist torque was set as constant, the passive joints were set in the lock state. On the other hand, we drove the slide joints manually because the present machine doesn't have sensors to measure Load distribution of wheels. So in the experiment, we drove them after front wheels had climbed up the step. This is shown in Fig.VII-I (3-4).

2) Results : When the velocity was 31mm/s or 250mm/s, the machine could climb up the step semi automatically as shown in Fig.VII-I. Focusing attention on the incident angles. In the case of a few degrees, the machine could not recognize the step because two wheels got contact with the step at the same time, so it could not climb up. In the case of over 10 degrees, the machine could climb up. When the angle became larger than a certain value, the order of wheels that climb up the step changed, even so it could climb up. The maximum angle the machine could climb up was about 80 degrees.

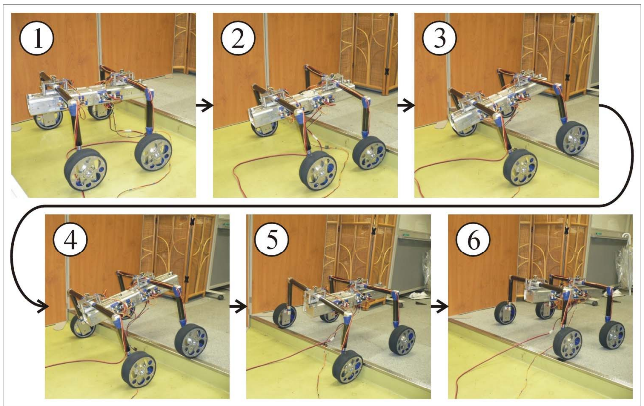


Fig. VII-I Scenery & Result of Experiment A

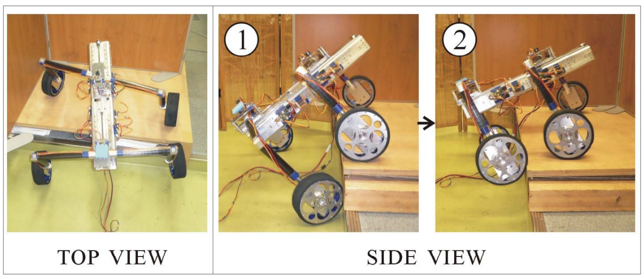


Fig. VII-II Scenery & Result of Experiment B

When the velocity was 500mm/s, after step-climbing of the second wheel, the wheel started to float from the ground and the third wheel could not climb up. The reason for this was the effect of the torque of wheels. It was also generated in other cases and reduced the loads of front wheels. But in this case, when the wheel contacts with the step, it became larger to keep the larger angler velocity of wheels. Therefore, beforehand we moved the COG forward and retried the experiment, all wheels could climb up the step.

B. *Confirmation of Effect of Leg Attitude*

1) Conditions : In this experiment, we confirmed that the effect of the leg attitude as explained in chapter V. The experiment scenery is as shown in Fig.VII-II. We conducted the experiment when the third wheel climbs up the step, because in this case the machine inclined the most. With the height-variable step, we determined the maximum height of the step the machine can climb up. In the experiment, the joint angles θ_f, θ_r were –30degrees and 0 (refer to Fig.V-III). And the command velocity was 31mm/s.

2) Results : The maximum height of the step that the machine could climb up was 230mm. So we confirmed the availability of the effect leg attitude.

VIII. CONCLUSION AND FUTURE WORKS

In this research, we proposed the new type of Leg-wheel hybrid quadruped mechanism, which could locomote on the rough terrain semi-automatically with the locomotion method based on the wheel locomotion. And we confirmed the availability of it experimentally with the real machine.

The future work is realizing full-automatic locomotion. Now the slide joints are driven manually. Therefore, in order to drive them automatically, we plan to add more sensors. And we also plan to make a new lock mechanism for the passive joints that can switch the state by the actuator, and propose how to control it automatically.

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