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Slip-suppression control for an electric crawler vehicle on an uphill path with low μ value

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Abstract

The sliding of heavy machines causes serious accidents in the construction industry. Slip is the main factor at work when machines slide. Conventional studies on preventing slip have focused on four-wheeled vehicles with tires, and conventional methods often use the rotational speed of the driven tires. Generally, electric crawler vehicles do not have driven tires. Therefore, we propose slipping suppression without using the rotational speed of driven tires. The proposed method uses only the electric current of drive motors to judge slipping. We conducted tests to confirm the effectiveness of the proposed method on a low-μ road. Experimental results confirmed the effectiveness of the method.

Keywords: Slip suppression control, Electric crawler vehicle, Low-μ road, Mechatronics, Tracked vehicle

1. Introduction

When heavy work machines slide, they can cause serious accidents in the construction industry. The main factor in sliding is slip. Fig. 1 shows the common causes of fatal accidents in the construction industry [1].

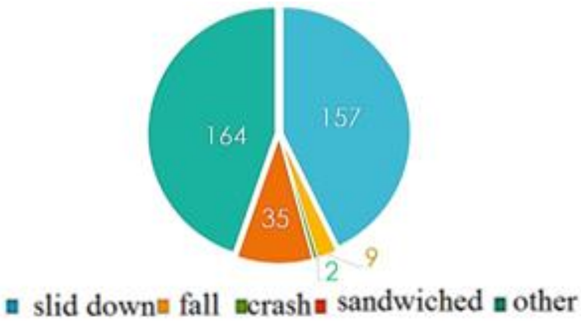


Fig. 1 Causes of death and injury in the construction industry

One of the causes of fall-crash accidents is heavy machinery slipping while running on a road surfaacae [2]. In the industry, heavy equipment must often travel on roads with poor surface conditions. Such conditions include wet or snowy surfaces, and so on. When wet asphalt pavement roads surfaces are compared to dry ones, the friction coefficient is reduced to one-fifth [3].Vehicle stability decreases on bad roads (hereafter, low-μ roads), and this can cause sliding. To address this problem, a technique to suppress slip on road surfaces has been reported. This technique can suppress slips between the wheel and ground, braking the drive wheel when the wheel slips. These systems detect wheel slip in the tires using the difference in rotational speed between the driving wheels and the driven wheels of four-wheel vehicles. However, electric crawler vehicles do not have driven wheels. Therefore, it is impossible to obtain the difference in rotational speed, and it becomes very difficult to detect slips in such vehicles. In this study, we propose a slip-suppression control method for electric crawler vehicles that uses neither vehicle speed nor wheel speed. We also demonstrate the effectiveness of the proposed method in low-μ road running experiments on wet slopes.

2. Slip-suppression control without using wheel or vehicle speed

Fig. 2 is a block diagram of the slip-suppression control system proposed in this study.

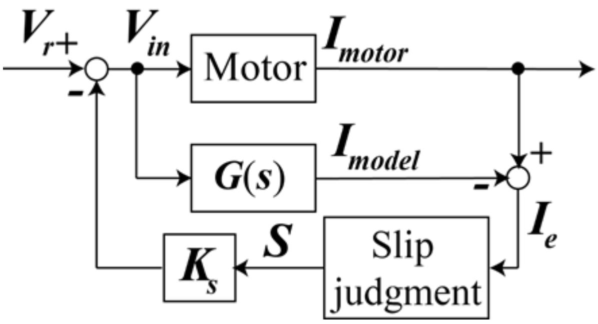


Fig. 2 Block diagram of the slip-suppression control

In the figure, V_r[V] is a reference voltage, V_{in}[V] is an applied voltage, I_{motor}[A] is the current of the DC motor, I_{model}[A] is the current of the model, I_e[A] is a current value error, and S[V] is a slip judgement value. The input of the system is the command voltage, and the output is the current of a DC motor. We can detect the slip between crawler and road surfaces using the slip judgement system. If the crawler vehicle slips due to an excess output of the DC motor, the slip judgement system outputs a slip judgement value. The slip judgment system detects the slip using the running-resistance of the electric crawler vehicle. Equation (1) shows the running resistance acting on the vehicle.

$$R = \mu mg\cos\theta + mg\sin\theta \qquad (1)$$

where R [N] is the running resistance, μ [-] is the coefficient of friction, m [kg] is the vehicle weight, g[m/s^2] is gravitational acceleration, and θ[deg] is the climbing angle. If the vehicle weight and uphill angle are constant, the running resistance changes due to the change in the coefficient of friction from equation (1). Running resistance is higher on high-μ roads, and vice versa. Slip-suppression control systems are mounted independently on each motor.

In this study, the current value was obtained from the motor of the mathematical model $G(s)$ at a current value and good running state of the motor to determine the slip. The motor mathematical model was identified using the input voltage and output current,

$$G(s) = \frac{I(s)}{E_a(s) + \frac{K_e T_L(s)}{Js + B_m}} = \frac{Ds + E}{As^2 + Bs + C} \qquad (2)$$

where E_a[V] is applied voltage, J[kg･m^2] is a moment of inertia, K_e[Vs/rad] is a back-emf constant, T_L [N･m]is load torque, and I is the armature current.

Table 1 lists the transfer function parameters of the motor identification.

Table. 1 Transfer function parameters of the motor identification

A	0.054
B	0.233
C	0.161
D	0.285
E	0.161

$$S = \begin{cases} -I_e & (\alpha > I_e) \\ 0 & (\alpha \le I_e) \end{cases} \qquad (3)$$

In Equation (3), α is a dead-zone threshold. In this paper, the value of α was set to 2.3 [A]. The current value of the DC motor in a crawler vehicle was varied when traveling on a low-μ road. Error of the value of the motor and model was generated by variation of the motor current value. The slip judgment was created by the error. The slip-suppression system mounts a dead zone to de-noise the sensor. Since here, α was set to 2.3 [A], motor output was reduced, due to the decrease of applied voltage using the slip determination value. The slip of the electric crawler vehicle according to the motor output suppressed slip on the road surface by controlling the output of the motor.

3. Experimental device

We explain the experimental apparatus in this section. Fig. 3 and 4 show the electric crawler vehicle. The experimental device used an electric crawler vehicle equipped with a DC brush motor. The left and right sides of the crawler were independently equipped with motors. Therefore, the vehicle was capable of moving freely. The experimental device was equipped with a current sensor for measuring the DC motor current (U.R.D.LTD, HCS-20-50-AS). At the time of the experiment we removed the chair of electric crawler vehicle for safety. Table 1 shows the specifications of the electric crawler vehicles. In this experiment, the yellow panel was used as a test course.

Fig. 3 3D CAD of electric crawler vehicle

Fig. 4 Experimental electric crawler vehicle

Table. 2 Specifications of electric crawler vehicle

Length [mm]	985
Width [mm]	900
Height [mm]	1250
Weight [kg]	90
Running speed [km/h]	6
Running distance [km]	20
Climbing ability [deg]	20
Weight capacity [kg]	200

4. Experimental Verification

We conducted a slip-suppression control experiment to test the proposed method on a low-μ uphill road. We used water on the test course to reduce its friction coefficient. We verified two approaches in the experiments, i.e., using the proposed slip-suppression control method, and not using the proposed method.

In the experiment, we measured the value of the DC motor current when the electric crawler vehicle was climbing. Fig. 5 shows the experimental results without slip suppression. In the figure, "t" means time. The electric crawler vehicle climbed on the test course at 2 s. however, the electric crawler vehicle attitude changed at 4 s in Fig. 5. The electric crawler vehicle slid down the test course at 5 s. As a result, the electric crawler vehicle could not climb the test course without the proposed system.

Fig. 6 shows the experimental results with the slip-suppression control. The electric crawler vehicle climbed the test course in 2 s, and 4 s. It finished climbing the test course in 5 s. If the vehicle attitude changed, the proposed method suppressed slip. There is no difference at 0-2 seconds between Fig. 5 and 6. However, there is a substantial change between 2-4 s. The crawler vehicle slipped on the test course when the DC motor output increased. We thus verified that vehicles could climb with the proposed method. Fig. 7 (a) shows the input voltage for the right side motor without the slip-suppression control. It shows a constant input without the proposed method. In contrast, Fig. 7 (b) shows the input voltage for the right side motor with the slip-suppression control. It decreased input of the DC motor, as proposed.

The control system can determine when a slip has occurred, because that suppresses input. Fig. 8 (a) shows the current for the right side motor without the slip-suppression control. It demonstrates that the motor current value falls below the model current value. Fig. 8 (b) shows the current for the right side motor with the slip-suppression control. Here, it can be observed that the motor current value increases at 2 s. It improves the traveling state by the slip-suppression control. Thus, these experimental results confirmed the validity of the slip-suppression control system in electric crawler vehicles by the proposed method.

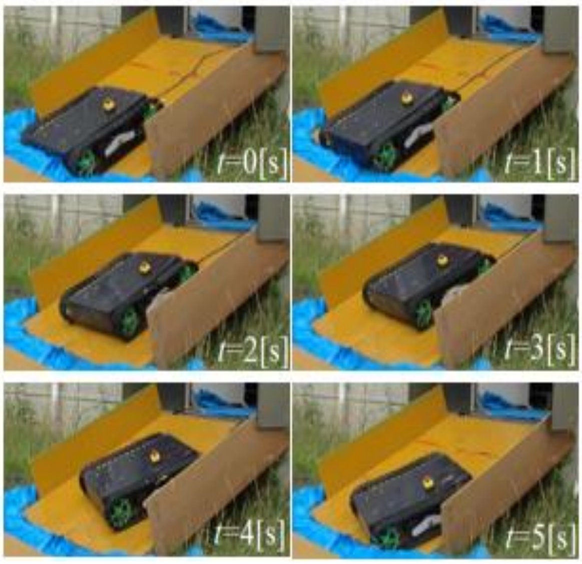


Fig. 5 Experimental results without slip-suppression control

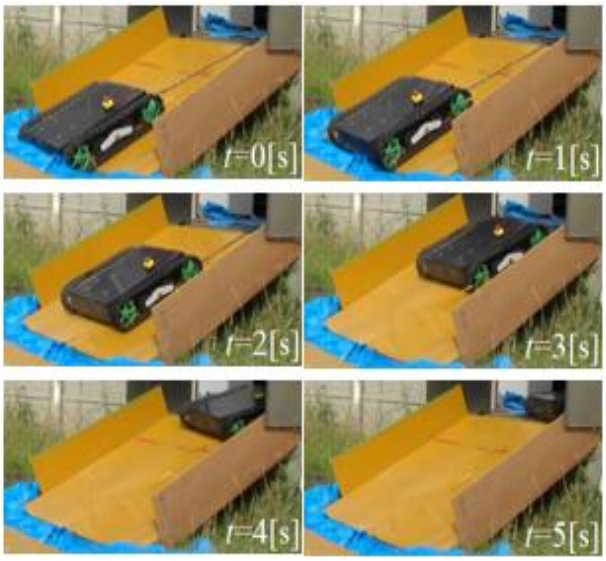
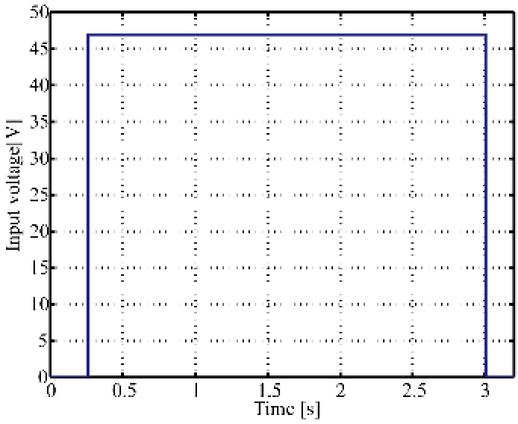
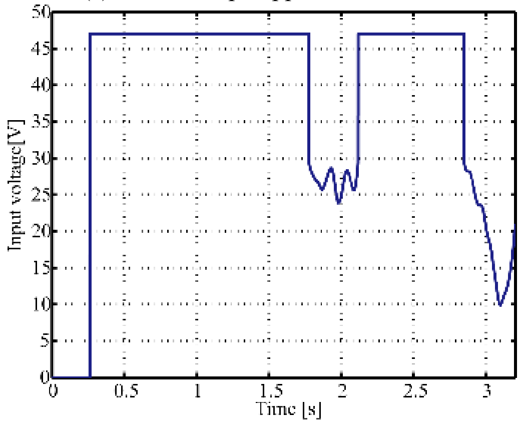


Fig. 6 Experimental results with slip-suppression control

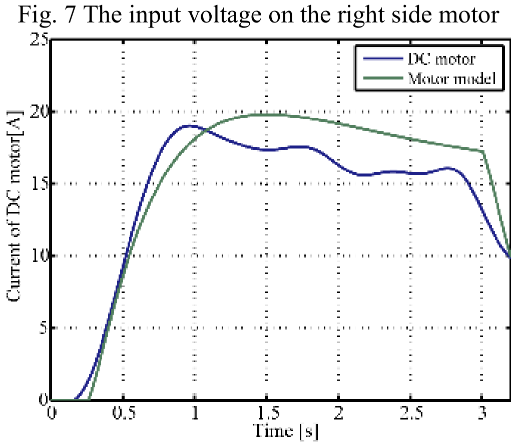


(a) Without slip-suppression control

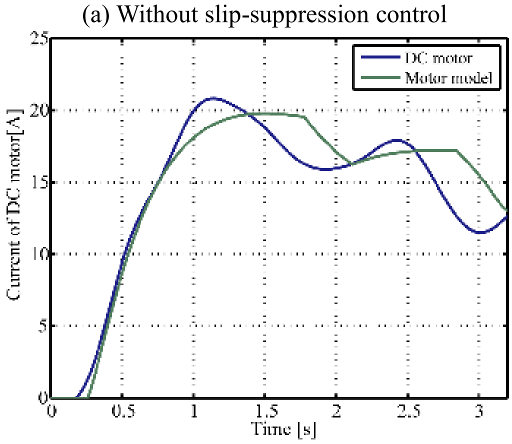


(b) With slip-suppression control

Fig. 7 The input voltage on the right side motor



(a) Without slip-suppression control



(b) With slip-suppression control

Fig. 8 The current of the right side motor

5. Conclusion

In the present study, we proposed a slip-suppression control system without the rotational speed of the driven tires in electric crawler vehicles. The proposed method uses the electrical current of the drive motors. A motor model of the ideal traveling state is used in the slip judgment system. The system determines the traveling state by comparing the model with the actual. We designed an experimental electric crawler device to test the system. The motor model was created based on it. We conducted tests in order to confirm the effectiveness of the proposed method on a low-μ road. In the experiment, it was difficult to climb the low-μ road without the proposed system. It was, however, possible to climb the test course when the proposed method was used. We therefore demonstrated the effectiveness of the proposed method with experimental results.

6. References

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