Online Estimation of Climbing Ability of Wheeled Mobile Robots on Loose Soil by Normal Stress Measurement

Keisuke Sato, Keiji Nagatani, and Kazuya Yoshida

Department of Aerospace Engineering, Tohoku University

Abstract :
To navigate a wheeled mobile robot on surfaces of planets covered with loose-soil, it is first necessary to estimate its climbing ability on sandy slopes. To estimate the drawbar pull of wheels, we have been developing a traction force model based on the distribution of normal stress, directly measured by pressure sensors attached at the surface of the wheels. In this study, we examine the abovementioned on-line estimation approach, and we verify the validity of this approach through experimentation.

応力測定センサを用いた軟弱地盤走行ロボットの登坂能力オンライン推定

佐藤 佳祐 永谷 圭司 吉田 和哉

東北大学大学院 工学研究科 航空宇宙工学専攻

概要：月・惑星の表面は軟弱地盤に覆われており，移動探査ローバーが安全な走行を行うためには，登坂能力 (斜面登坂に必要とされるけん引力に対する滑り度) を事前に予測することが非常に重要である．本研究室では，応力測定が可能なセンサを内蔵した車輪を利用し，直接車輪に加わる応力分布を測定することによる駆動力発生モデルの構築を行ってきた．本稿では，このけん引力モデルならびに応力測定センサを利用したオンラインでの登坂能力推定手法を検討すると共に，その有用性について検証する．

1. Introduction

In lunar and planetary exploration, mobile robots, which are called rovers, have considerable advantage for conducting direct probes in a wide area. However, because the target environment is covered with fine sand, wheel slippage becomes an obstacle to its smooth navigation. Slippage makes it difficult to follow a desired path. In the worst case, the wheels become stuck in the ground, resulting in mission failure. The above situation usually occurs when the rover climbs up slopes, such as the side of craters. To avoid such situations, it is very important to understand the wheel-soil interaction and to estimate the drawbar pull of the wheels before the mission is undertaken.

An analysis based on wheels-soil interaction clarifies the behavior of the wheels on loose ground. Such "terramechanics" studies conducted by J.Y.Wong, M.G.Bekker, and others in the 1960s, and various dynamical models have been constructed based on the terramechanics [1] [2]. However, it is difficult to apply these approaches directly to an exploration rover in unknown environments, such as a planetary surface. The reasons are that most of these terramechanics models assume flat terrain and uniform soil (whereas the target environment has neither) and require that various soil parameters are known beforehand, which is practically impossible.

To overcome this situation, we have examined terramechanics-based estimation of climbing ability in unknown environments, and have reviewed the drawbar pull model based on terramechanics. One of the features of our research is the use of built-in force sensor array (BFSA) wheel that measures normal stress distribution with an array of pressure sensors attached to the surface of a wheel. In our initial test using the BFSA wheel, we found an interesting phenomenon. The normal stress was not distributed over the entire contact face, ; instead, it was found only at the front part of the contact face [5]. Furthermore, as the slip ratio increases, the distribution moves to the front part of the wheel. However, conventional models have not been able to describe such phenomena. Therefore, we developed a new on-line method to estimate soil parameters for obtaining the drawbar pull based on the measurement of normal stress distributions [5]. It made it possible to reduce the number of required estimation parameters, and result in more accurate on-line estimation. However, this method always requires the measurement value of normal stress distributions. Therefore, the drawbar pull of the rover cannot be estimated if the rover has not yet traversed any terrain.

In this study, we aim to develop the on-line estimation of climbing ability that estimates the drawbar pull in areas that the rover has not traversed yet. In other words, we develop an elemental technology to

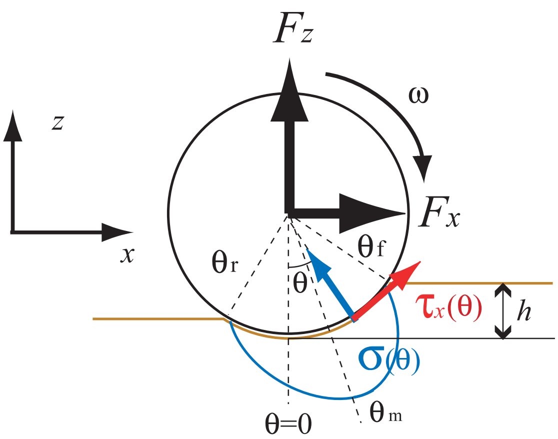


Fig. 1: Wheel-soil contact model

estimate the drawbar pull under conditions of high slippage (on a steep slope) based on data obtained under low-slippage conditions (on a gentle slope).

This paper is organized as follows. The drawbar pull model based on terramechanics is introduced in Section 2. The measurement experiments of normal stress distribution using the BFSA- wheel are reported in Section 3. The elements required for online estimation of climbing ability are presented in Section 4. A method for the estimation of normal stress distribution based on the actual measurement value is described in Section 5. A method for the identification of the required parameters is proposed in Section 6. A method used for the online estimation of climbing ability using the above methods is described in Section 7.

2. A drawbar pull model of a wheel traversing loose soil

In this section, we introduce the drawbar pull model of a wheel that traverses loose soil based on the terramechanics and shear stress model. The shear stress is a very important element required for drawbar pull estimation.

2.1 Drawbar pull model

The drawbar pull of a wheel rotating on loose soil is determined by

$$F_x = rb \int_{\theta_r}^{\theta_f} \{\tau_x(\theta)\cos\theta - \sigma(\theta)\sin\theta\} d\theta, \qquad (1)$$

where r and b are the wheel radius and width, respectively. As shown in (Fig. 1), θ_f and θ_r are the entry and exit angles based on downward vertical direction. From this equation, drawbar pull F_x is calculated by integrating normal stress $\sigma(\theta)$ and shear stress $\tau_x(\theta)$ from the entry angle θ_f to the exit angle θ_r.

2.2 Shear stress model

In this study, the following equation (2), formulated by Janosi and Hamamoto [4], is used as a shear stress model.

$$\tau_x(\theta) = (c + \sigma(\theta)\tan\phi)[1 - e^{-j_x(\theta)/k_x}], \qquad (2)$$

In this equation, the soil deformation j_x can be formulated as,

$$j_x(\theta) = r[\theta_f - \theta - (1-s)(\sin\theta_f - \sin\theta)] \qquad (3)$$

where, c and ϕ represent the cohesion stress and the internal friction angle of the soil, and k_x is the shear deformation module which depends on the shape of the wheel surface and type of soil. Furthermore, s, called the slip ratio, can be calculated as below, using the translational velocity of the robot v_x and the rotational velocity of wheel $r\omega$.

$$s = \begin{cases} \frac{r\omega - v_x}{r\omega} & (r\omega > v_x : \ driving) \\ \frac{r\omega - v_x}{v_x} & (r\omega < v_x : \ breaking) \end{cases} \qquad (4)$$

3. Measurement experiments of normal stress distribution

In order to analyze the trend of normal stress distributions that are generated under the wheel, measurement experiments of normal stress distribution using pressure sensors were carried out. In this section, the experimental methodology and the measurement trend of the normal stress distributions are reported.

3.1 Overview of experimental setup

In this experiment, a relationship between slip ratio and normal stress distribution was measured by performing experiments using our four-wheeled mobile robot (El-Dorado II) with the BFSA-wheel [5] (Fig. 2) attached to the surfaces of the right-rear wheel and the right-front wheel. To measure the above relationship under different conditions, we used our experimental field (width: 1.0 [m], length: 2.0 [m]) that could be set to various slope angles (Fig. 3).

The BFSA-wheel makes it possible to obtain normal stress distributions by measuring the normal

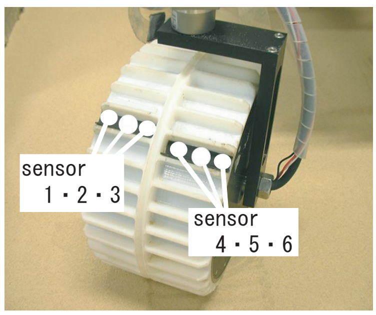


Fig. 2: BFSA-wheel

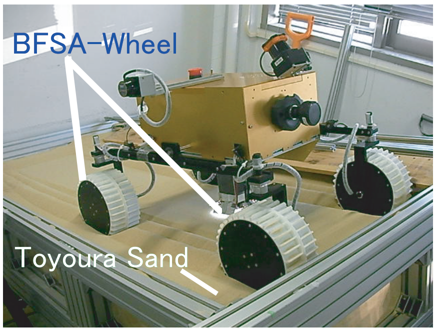


Fig. 3: Test bed and test field

stress continuously while it rotates. The wheel can also obtain rough distributions of normal stress in the width direction by installing six pressure sensors in the width direction.

Slip ratio was calculated by Equation (4), using the translational velocity of the robot v_x and the rotational velocity of the wheel $r\omega$. v_x was measured by a TMMS (telecentric motion measurement system [5]). The TMMS is a device that measures the robot's velocity using a visual odometry technique, which was developed by our research group. ω was measured by encoders installed in the driving motors.

The rotational velocity of the wheels was set at 9.15 [mm/s]. The order of the velocity was the same as that used in an actual planetary exploration. At each slope angle (0, 4, 8, 10, 12 [°]) of the field, the experiments were repeated four times. The experimental field contained Toyoura standard sand (JIS R 5201), which has very low viscosity ($c \approx 0$) and whose particles are almost uniform.

3.2 Experimental results

Figure 4 shows an example of the experimental result of obtained normal stress distributions. It shows the average of normal stress distributions when the slope angle is equal to 4 [°]. In this figure, the positive direction of the wheel angle is defined as the forward direction of the wheels, and the wheel angle is equal to 0° when it is in the vertical direction. This figure shows that the normal stress is not distributed over the entire tread of the wheel, but distributed only in the front area. Meanwhile, Fig. 5 shows a relationship between slip ratio and normal stress distributions. This figure also shows that the normal stress distribution moves toward the front, in accordance with the increasing slip ratio.

Since the normal stress on weak ground has been cinsidered to be distributed over the entire tread of the wheel, the above tendencies cannot be expressed by conventional models, such as Bekker's model. Therefore, we determined that we would not use a conventional model as normal stress distribution, for estimating drawbar pull. Instead, our proposed model is based on the direct measurement value of normal stress using a BFSA-wheel.

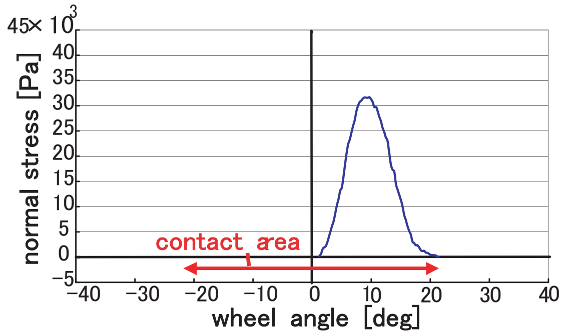


Fig. 4 : Experimental result of a normal stress distribution (rotation direction)

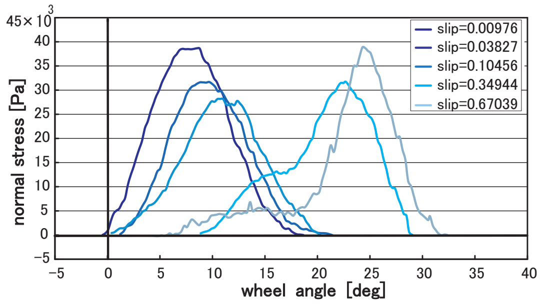


Fig. 5 : Relationship between slip ratio and normal stress distribution

4. Elements required for online estimation of climbing ability

In this section, the elements required for online estimation of climbing ability are presented. We define the climbing ability as the relationship between the slip ratio and the drawbar pull that is required for climbing up the slope. This implies that relationship between the slip ratio and the drawbar pull on steeper slope should be estimated by using the data obtained from gentle slopes or flat conditions to estimate climbing ability online. There are three elements for the parameter estimation:

1. Construction of a normal stress distribution model based on measurement values of normal stress.
2. Estimation of the relationship between the slip ratio and the normal stress distribution under gentle slope conditions.
3. Identification of various soil parameters required for drawbar pull calculation based on Equation (1) under gentle slope conditions.

We introduce the above elements in the following sections.

5. Estimation of normal stress distribution

Since conventional models of normal stress distributions are difficult to apply to our situation, we propose a new model based on the measurement value of normal stress using a BFSA-wheel. However, there are two problems. The first one is the normal stress distribution in the width direction. The second one is the transition of distributions in accordance with slip ratio variation. In this section, we would like to discuss the above two problems that need to be solved.

5.1 Estimation of total normal stress

As shown in Fig. 2, six pressure sensors are attached to the flat part of the wheel between the traction lugs. The sensing area of each sensor is a circular shape whose diameter is 9.5 [mm]. At these settings, presently, BFSA-wheels cannot measure the stress on the traction lugs. Furthermore, it is difficult to obtain a high resolution of the normal stress distribution in the direction of wheel width. Even if experiments are performed under the same conditions, the measurement values of normal stress may change drastically. That is because the distribution in the wheel's width direction may be changed by small differences in the terrain and rover's posture. Meanwhile, when the slope angle was the same, it was found that the shapes of the distributions measured by each sensor were almost the same. This implies that the shapes of the distributions are similar in the width direction of the wheels, and the difference of each distribution is the only absolute value.

To estimate drawbar pull, the important thing is to estimate the shape of the distribution in the circumferential direction and the total amount of the normal stress. The total amount of the normal stress is calculated as a product of the average normal stress and the wheel width, since the shapes of the distributions are similar in the width direction. In other words, an estimate of the averaged normal stress distribution makes it possible to estimate the drawbar pull.

On the basis of the above method, we propose a method to define normal stress distributions, shown as Equation (5). This equation implies that an average of normal stress distribution can be calculated as a product of the measured shape of distribution $\sigma_s(\theta)$ and the constant parameter M.

$$\sigma(\theta) = M\sigma_s(\theta) \tag{5}$$

5.2 Estimation of normal stress distribution in accordance with slip ratio variation

Approach

As shown in Fig. 5, the normal stress distribution moves to the front area of the wheel in accordance with increasing the slip ratio. In order to estimate a normal stress distribution on a large slope angle, we propose a method to generate the artificial high slip ratio on a flat surface by rotating front and rear wheels at different rotational velocities.

In this method, typically, the wheels with the high slip ratio sink deeper than the wheels in the low slip ratio, which causes the rover not to be parallel to the surface of the ground. To measure the inclination of the body and the sinkage of the wheels, we used a laser range finder mounted at the side of the robot (Fig. 6).

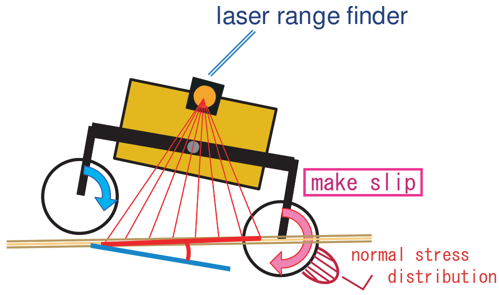
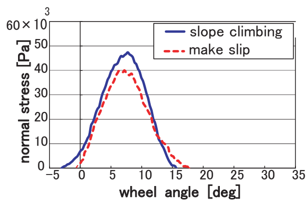
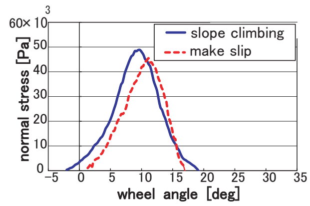


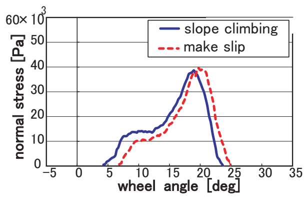
Fig. 6 : An overview of causing slippage by making the slip ratio diffrent between front and rear wheel velocity



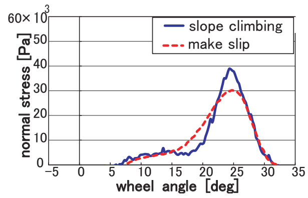
(a) [slope climbing : slip=0.03827]
[make slip : slip=0.03827]



(b) [slope climbing : slip=0.10456]
[make slip : slip=0.12732]



(c) [slope climbing : slip=0.34944]
[make slip : slip=0.37253]



(d) [slope climbing : slip=0.67039]
[make slip : slip=0.68865]

Fig. 7 : Comparison of normal stress distribution for each slip ratio

Verification test

To confirm the validity of the above method, verification tests were carried out using the same test bed and experimental field that were used for the experiment described in the previous section. The rotational speed of the front wheels was set at 9.15 [mm/s], equal to the speed used in the previous experiments. Meanwhile, the rotational speed of the rear wheels was set at lower speed than that of the front wheels, in order to generate artificial slip ratios. The slip ratios 0.04, 0.13, 0.36, and 0.68 were set up in these experiments, and experiments were carried out five times under each condition.

Figure 7 shows the experimental results. In each slip ratio, the normal stress distribution measured in slope climbing motion was almost the same as the normal stress distribution generated by different rotational speeds of wheels on a flat surface. This implies that the shape of a normal stress distribution on a slope can be estimated by generating artificial slips on a flat surface. The proposed estimation approach was thereby validated.

6. Identification of parameters

In this section, our method of identifying parameters is introduced, and one estimation example using the method is reported.

To estimate drawbar pull, both normal stress and shear stress should be obtained. In this study, Equation (5) is employed as the normal stress model. Because the number of parameters to identify is fewer than Bekker's model, we can say that this model is a more practical method. On the other hand, Equation (2), formulated by Janosi and Hamamoto, is employed as a shear stress distribution [4], keeping in mind that $\sigma(\theta)$ is also contained in Equation (2). In these equations, only c (the cohesion stress), ϕ (the internal friction angle of the soil), k_x (the shear deformation module), and M (the constant parameter) are the parameters that are required to be estimated.

6.1 Approach

When a rover climbs up a slope of α [°], drawbar pull F_x and vertical forceF_z can be expressed in following equations:

$$F_x = mg\sin\alpha, \quad (6)$$
$$F_z = mg\cos\alpha, \quad (7)$$

where F_{x_n} and F_{z_n}, acting on each wheel, are calculated by integrating $\sigma_n(\theta)$ (Equation (5)) and $\tau_{x_n}(\theta)$ (Equation (2)) in the stress-generated range:

$$F_{x_n} = rb\int_{\theta_{r_n}}^{\theta_{f_n}} \{\tau_{x_n}(\theta)\cos\theta - M_n\sigma_{s_n}(\theta)\sin\theta\}d\theta, \quad (8)$$
$$F_{z_n} = rb\int_{\theta_{r_n}}^{\theta_{f_n}} \{\tau_{x_n}(\theta)\sin\theta + M_n\sigma_{s_n}(\theta)\cos\theta\}d\theta. \quad (9)$$

In this study, we assume that the forces acting on both side wheels are bilaterally symmetric because the terrain is flat in the cross direction. Therefore, the drawbar pull of the front wheel (F_{x_f}), the drawbar pull of the rear wheel (F_{x_r}), the vertical force of the front wheel (F_{z_f}), and the vertical force of the rear wheel (F_{z_r})satisfy the following condition:

$$F_x = 2(F_{x_f} + F_{x_r}), \quad (10)$$
$$F_z = 2(F_{z_f} + F_{z_r}). \quad (11)$$

The slope angle α was measured using the mounted gyroscopes and the acceleration sensor. The wheel radius r and the wheel width b were given. The slip ratio for the calculation in j_x was obtained by Equation (4) using the translational velocity of the robot v_x and the rotational velocity of wheel $r\omega$. v_x was measured using a TMMS [5], and ω was measured by encoders installed in the wheels. In addition, θ_f and θ_r were measured using the BFSA-wheel.

As a result, two equalities were derived from Equations (6) and (10), and Equations (7) and (11). These two equations are independent under each slope angle condition. Thus, c, ϕ, k_x, and M can be identified by more than three experiments in different conditions, theoretically. Here, M is an intermediate parameter for estimating the average normal stress from measured values. Therefore, it is important to identify c, ϕ, and k_x.

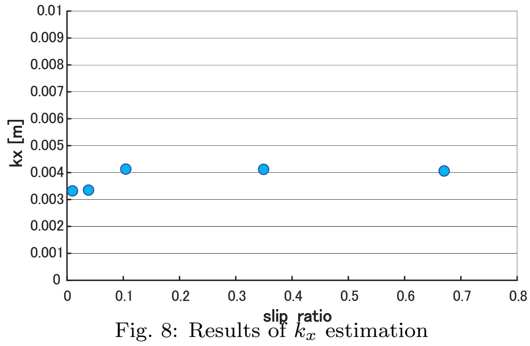


Fig. 8: Results of k_x estimation

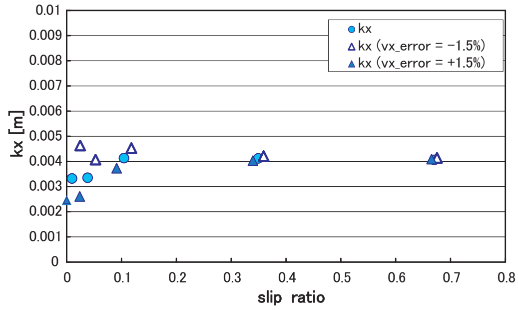


Fig. 9: Effect of sensor error for k_x estimation

To simplify the problem in this study, c and ϕ were given in advance, ($c = 0$ [KPa] and $\phi = 38.0$ [°]).

6.2 Identification results

Figure 8 shows the identification results for k_x. Identification was carried out using the experimental data shown in Section 3. We can see that k_x stays almost constant against the slip ratio (slope angle). Since k_x is the parameter that depends on soil conditions and the surface of the wheel, it should be constant. Based on the above, the results verified the usefulness of the proposed method.

Figure 9 shows the identified values in cases where the measurement value v_x includes a sensing error of −1.5% and +1.5%. These values are the theoretical error range for the TMMS.

As shown in Fig. 9, k_x is sensitive within the low slip ratio range. That is because the error of the slip ratio depends considerably on the sensing error of the velocity in the low slip ratio range and because the shear stress, $\tau_x(\theta)$, uses this value.

7. Estimation of climbing ability

In this section, an online approach to estimating climbing ability, and a relevant example are introduced.

7.1 Approach

According to the previous section, a relationship between the drawbar pull F_x and the slip ratio should be obtained in order to estimate climbing ability. In this study, we estimated the relationship in the case of two slope angles: 0 [°] and 4 [°]. Keep in mind that, to simplify the problem in this study, again, c and ϕ were given in advance (c = 0 [KPa] and ϕ = 38.0 [°]). The estimation is performed by the following procedure.

1. **To identify various parameters using the method proposed in Section 6.1 under a gentle slope condition**

   In the case of a gentle slope condition, some sets of relationships between the slip ratio and the drawbar pull are obtained in the first step. Since the soil parameter is independent of the slip ratio, some soil parameters, such as k_x, are obtained using the sets of data by averaging of them.

2. **To measure the relationship between the slip ratio and $\sigma(\theta)$ using the method proposed in Section 5 under a gentle slope condition**

   To estimate a drawbar pull under steep slope conditions, some sets of relationship between the slip ratio and $\sigma(\theta)$ are obtained by the method proposed in Section 5 under a gentle slope condition. The graphs in Fig. 5 are examples based on this method.

3. **To estimate a drawbar pull in the slip ratio specified in step 2 using Equation (10)**

   Some sets of relationships between the slip ratio and the drawbar pull are estimated using soil parameters (obtained in step 1) and the relationships between the slip ratio and the $\sigma(\theta)$ (obtained in the step 2). Fig. 10-(a) is an example graph that shows some sets of relationships between the slip ratio and the estimated drawbar pull.

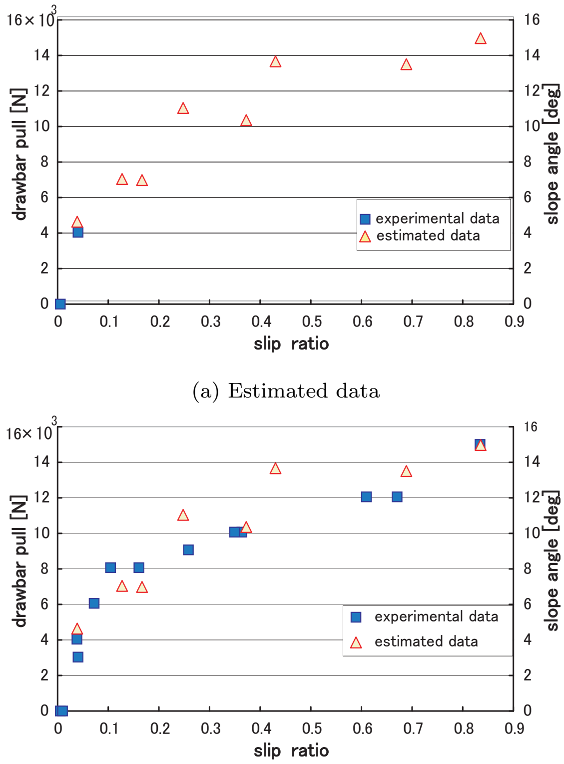
Figure 10-(b) shows a comparison between the estimated drawbar pulls based on the above approach and measured drawbar pulls. As shown in the Fig. 10-(b), the trend of estimation results almost fits the experimental data. This validates the usefulness of the above approach. As mentioned in Section 6.2, soil parameters can be identified accurately in cases in which the rover uses a higher slip ratio to estimate the value.

8. Conclusion

In this paper, a method for estimating the climbing ability on-line of wheeled mobile robots was presented.

Regarding the normal stress required for the estimation of drawbar pull, the experimental results using a BFSA-wheel showed that the description of the normal stress distribution is difficult to express using conventional models. Therefore, a method to estimate the normal stress distribution using directly measured values was proposed. Furthermore, an approach using the identification of various soil parameters to calculate drawbar pull was proposed. The identification results verified the usefulness of the above method. A sensitivity analysis was also discussed. Finally, an online estimation approach for climbing ability using the above methods was presented. That approach was validated through some verification tests.

In our future work, we would like to confirm the usefulness of the proposed approach using different types of wheels and soils. In addition, we would like to apply the proposed approach to investigate the side slippage conditions of wheels.



(a) Estimated data

(b) Comparison of estimated and experimental data

Fig. 10: Estimation of climbing ability

References

[1] M.G.Bekker : "Off-The-Road Locomotion," Ann Arbor, MI, USA, *The University of Michigan Press*, 1960.

[2] J.Y.Wong : "Theory of Ground Vehicles," John Wiley & Sons, 1978.

[3] M.G.Bekker : "Introduction to Terrain-Vehicle Systems," Ann Arbor, MI, USA, *University of Michigan Press*, 1969.

[4] Z.Janosi, B.Hamamoto : "The analytical determination of drawbar pull as a funcition of slip for tracked vehicle," *Proc of the 1st Int. Conf. on Terrain-Vehicle Systems*, Torio, 1961.

[5] K.Nagatani, A.Ikeda, K.Sato K.Yoshida : "Accurate Estimation of Drawbar Pull of Wheeled Mobile Robots Traversing Sandy Terrain Using Build-in Force Sensor Array Wheel," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp.2373-2378, 2009