SLIP COMPENSATED ODOMETRY FOR A TRACKED VEHICLE WHEN ROTATING ON A LOOSE WEAK SLOPE

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Abstract

Slip-compensated odometry based on the slip estimation method of a tracked vehicle is proposed to improve the accuracy of position estimation. While a robot travels on a loose and weak slope, it slips longitudinally and laterally, particularly when rotating. These slips introduce error in odometry, and it is difficult to use odometry in controlling a robot and recognition of an environment such as trajectory following and three-dimensional mapping. In this paper, we describe a method of estimating these slips with inertial information, rotation velocity of the tracks employing a simple regression function. We confirmed that previous work of estimating longitudinal slippage on a horizontal plane can be applied for a weak slope. Estimation of lateral slippage is based on a regression analysis using offline training data of a robot's travel on a slope. This regression technique can be used online using information from a global navigation satellite system or other sensors. We applied these slip estimation methods to a kinematic model of a skid-steering tracked vehicle for odometry, and confirmed the improvement in precision of odometry compared with conventional odometry by conducting indoor sandy-slope experiments. We also proposed a path following control law considering lateral slippage, and confirmed the effectiveness of the control law in experiments.

Keywords: Odometry, slip estimation, skid-steering tracked vehicle

1. Introduction

Japan experiences many natural disasters and requires countermeasures against such disasters. Currently in Japan, the eruption warning level exceeding level 2 where the entry of 1 km around is restricted has reached 10 (Japan Meteorological Agency). Pyroclastic flows and other disasters may occur around volcanoes, and it is therefore difficult for people to enter volcanic areas. Unmanned robots are thus expected to explore such areas and observe the statuses of volcanoes.

A ground vehicle will slip while traveling through a volcanic field, because volcanic areas are soft and irregular sites covered with rocks and volcanic ash. Such slippage causes problems in position estimation by odometry and path following control. Odometry is a basic method of estimating the position of a vehicle by integrating the rotation velocity of wheels or tracks. Slippage therefore introduces error in positioning. To estimate slippage, several studies have adopted a terramechanics-based approach (Ding et al. 2009) (Yoshida et al. 2002) or inertial-information-based approach. In employing the terramechanics approach, stress and forces are considered with values of terrain parameters (Wong 2008). The determination of parameters requires large-scale experiments, and this method is therefore mainly used in known environments (Terzaghi et al. 1996). Taking the inertial-information-based approach, Endo et al. (2007) proposed an empirical formulation of the slip ratio and rotation velocity. This method can be applied to a skid-steering tracked vehicle traveling on rigid ground, and it estimates the slippage of each track. However, it targets only the longitudinal slippage without the lateral slippage.

Slippage affects not only the odometry but also path following because conventional path following for a ground vehicle employs a feedback control system based on the position and orientation of the vehicle. In this paper, following Endo's approach, we integrated the lateral slippage estimation through regression analysis with internal information such as that of the orientation and velocity. We also propose a slip-prediction path following method that exploits the slip-compensated odometry.

2. Slip-compensated odometry for skid-steering robots

2.1 Kinematics of a skid-steering mobile robot including slippage

On the basis of previous methodology (Endo et al. 2007), we introduce the kinematics of a skid-steering mobile robot including longitudinal and lateral slippage. Figure 1 shows a skid-steering tracked vehicle traveling on a plane surface with slippage. When the right and left tracks rotate, longitudinal and lateral translational velocities V_x and V_y in the robot coordinate system Σ_r are

$$V_x = \frac{v_r(1-\alpha_r) + v_l(1-\alpha_l)}{2} \tag{1}$$

$$V_y = V_x \cdot \tan\beta \tag{2}$$

where α_r and α_l are the slip ratios of the two tracks, β is the slip angle and v_r and v_l are input velocities that can be measured by encoders. The slip ratios of the tracks are defined as

$$\alpha_r = 1 - \frac{v_r^{\prime}}{v_r} \tag{3}$$

$$\alpha_l = 1 - \frac{v_l^{\prime}}{v_l} \tag{4}$$

where $v_r^{\prime}$ and $v_l^{\prime}$ are ground velocities. If the robot runs without slippage, the ground velocity equals the input velocity and the slip ratio is zero. V_x and V_y are the ground velocity components of the robot base, and the kinematics of the tracked vehicle can therefore be derived as

$$\dot{x} = V_x\cos\theta - V_y\sin\theta \tag{5}$$

$$\dot{y} = V_x\sin\theta - V_y\cos\theta \tag{6}$$

$$\dot{\theta} = \omega = \frac{v_r(1-\alpha_r) - v_l(1-\alpha_l)}{2d} \tag{7}$$

where θ is the angle of rotation, 2d is the distance between the tracks, and ω is the angular velocity. The slip-compensated odometry is calculated to integrate from the kinematics expressed in Eqs. 5–7.

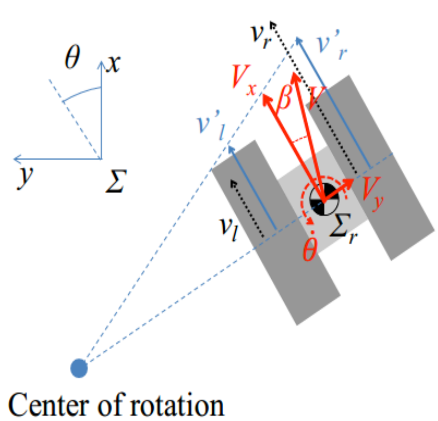

Fig. 1. *Kinematics of a skid-steering tracked vehicle*

2.2 Method of estimating the slip ratio and slip angle

The kinematics given in Eqs. 5–7 exploit the slip ratio and slip angle to estimate the longitudinal and lateral translational velocities. To determine the slip ratio, Endo (2007) proposed the equation

$$\frac{\alpha_l}{\alpha_r} = -sgn(v_r \cdot v_l)\left(\left|\frac{v_r}{v_l}\right|\right)^n \quad 8$$

where n is an empirical number that depends on the rotation traveling experiment. If the angular velocity can be measured by sensors (i.e., gyroscope sensors), the slip ratio can be obtained from Eqs. 7 and 8. The parameter n is known to be constant for a horizontal solid plane. However, n has not been confirmed for loose terrain or a slope. The verification of the parameter for such fields is described in Section 2.3.

Meanwhile, to estimate the lateral translational velocity, the longitudinal translational velocity and slip angle should be determined. The longitudinal translational velocity can be obtained from Eq. 1. We introduce a method of estimating the slip angle. When a robot rotates on a loose slope, a lateral force acts on the robot. This force consists of a bulldozing resistance acting on the sides of the tracks, a shear resistance that rotates the robot acting on the bottom of the tracks, and the robot's weight acting parallel to the slope. The bulldozing resistance is derived from soil parameters, the rotation resistance, the angular displacement of the robot, and the configuration of the robot. The shearing resistance is obtained from the rotation radius, angular displacement, and configuration of the robot. The robot's weight parallel to the slope is calculated from the roll angle and the mass of the robot. If the terrain is homogeneous and soil parameters do not change, then the lateral force is derived from the roll angle, angular displacement, and rotation radius. Note that the angular displacement is the angle from the starting orientation of the rotation movement.

In this study, we conduct multiple linear regression analysis to estimate the slip angle, using the roll angle, angular displacement, and rotation radius as explanation variables. The regression function is

$$\beta = \sum_{i=1}^{4} a_i X_i \quad 9$$

where X_i is i-th explanation variable and a_i is the i-th coefficient of the variable. In addition, X_1 takes the value 1 and a_1 is the intercept of the linear regression function. The coefficients are identified using a training data set and minimizing the squared error:

$$R = \sum_{i=1}^{k} (B_i - \beta_i)^2 \quad 10$$

where k is the number of training data, B_i is the i-th true slip angle, and β_i is the i-th prediction made using Eq. 9. The odometry can be calculated by applying Eqs. 8 and 9 to the kinematics.

2.3 Experimental setup for the verification of slip-compensated odometry

To confirm the slip parameter n for the loose plane and loose slope and to verify the method of estimating the slip angle by regression analysis, we conducted various rotation experiments on a sandy loose field as shown in Figure 2. The field was filled with Toyoura sand and had length of 2 m, width of 1 m, and depth of 0.2 m. The field could be tilted from 0 to 15 degrees by jacking up one side of the field. We used the skid-steering tracked vehicle Patako (shown in Figure 3) as the testbed. The specifications of the robot are given in Table 1. The parameter $\boldsymbol{n}$ was identified as 0.824 on a solid linoleum floor.

Table 1. Specifications of the testbed

Dimensions [mm]	Mass [kg]	Tread [m]	Track length [m]	Track width [m]	***n*** *(*solid floor*)*
L503 × W686 × H522	0.41 [m]	0.41	0.60	0.11	0.824

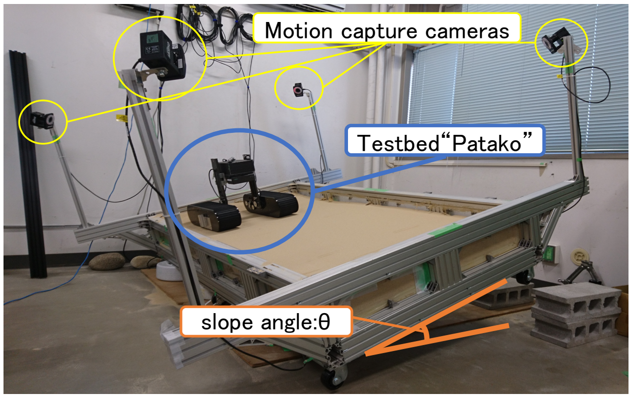

Fig. 2. *Experimental Field*

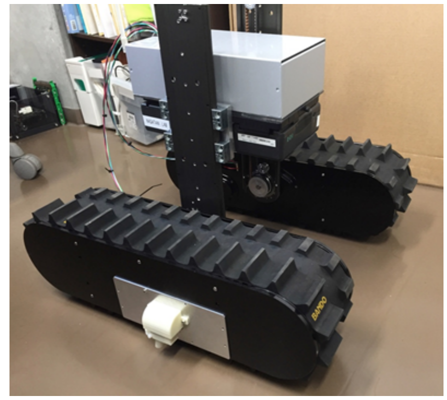

Fig. 3. *Skid-steering tracked vehicle test-bed*

In the experiments, the robot was set parallel to the long side of the field as shown in Figure 2, and it rotated through an angle of about 90 degrees. The actual movement and orientation were measured by an Osprey motion-capture camera, installed at the corner of the experimental field. The slip ratio and slip angle were obtained as derivatives of the measurement data. The tilt angle of the field was varied at 0, 8, and 15 degrees. The velocity of the robot was set at 5 cm/s, and the angular velocity was set at 10, 20, and 30 deg/s.

2.4 Experiment results

To estimate the slip ratio, the parameter $\boldsymbol{n}$ was identified from the results shown logarithmically in Figure 4 for each condition. The horizontal axis gives for the ratio of each track's velocity $\frac{v_r}{v_l}$ while the vertical axis gives the ratio of each track's slip ratio $\frac{\alpha_l}{\alpha_r}$. The parameter $\boldsymbol{n}$ is calculated from the logarithmic approximation employing the least-squares method. The parameter $\boldsymbol{n}$ is 0.832 at a tilt angle of 0 degrees, 0.817 at 8 degrees, and 0.824 at 15 degrees. For each condition, the parameter $\boldsymbol{n}$ did not vary in the experiments.

According to the regression function (Eqs. 9 and 10), the coefficients of the explanation variables were determined using the experimental results as training data. Figure 5 shows the results of the estimated slip angle and ground truth recorded by the motion-capture system. In the figure, the estimated slip angle follows the change in the ground truth, and the designed regression function thus approximately represents the slip angle. Finally, the position estimation results are shown in Figures 6A and 6B. The results are compared with the ground truth and the results of other position estimation methods, namely gyrodometry and conventional odometry. Gyrodometry is calculated using the velocity from the encoders in the tracks and the orientation from the gyroscope (Borenstein 1996) while conventional odometry is the estimation method of Endo et al. (2007). The position determined by gyrodometry corresponds to a longer distance traveled than the other results. This is because gyrodometry does not consider longitudinal and lateral slippages. Meanwhile, the conventional method only includes the longitudinal slippage and there are thus errors mainly in the Y-position. We found the accuracy is improved by 82% in terms of the root-mean-square error compared with gyrodometry.

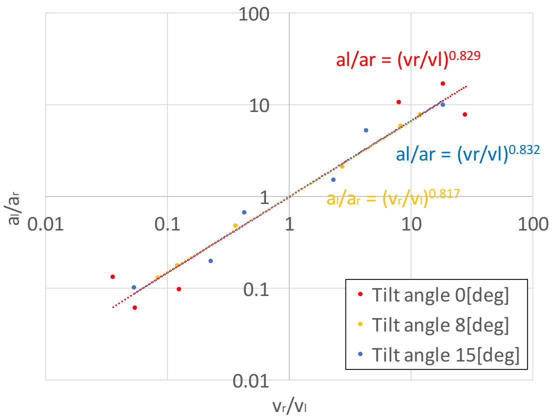

Fig. 4. *Ratio of the velocity and slip ratio of each track. Red dots are the results for a tilt angle of 0 degrees, blue dots are those for 8 degrees, and yellow dots are those for 15 degrees.*

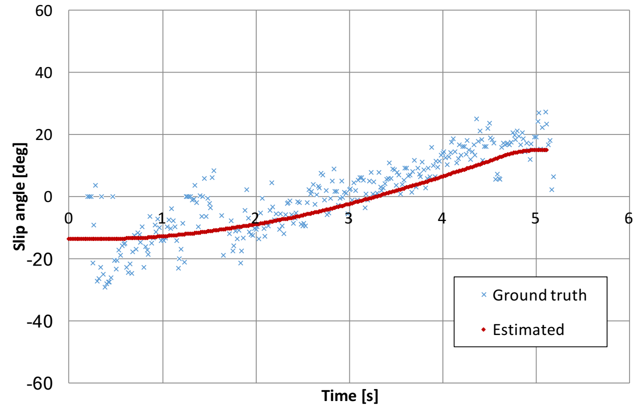

Fig. 5. *Slip-angle estimations. The red line is the estimated value while blue dots are the ground truth.*

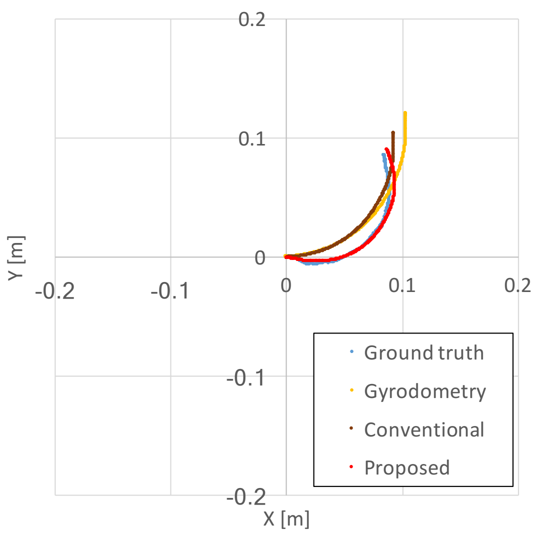

Fig. 6A *Estimated position for a tilt angle of 8 degrees and a target angular velocity of 30 deg/s.*

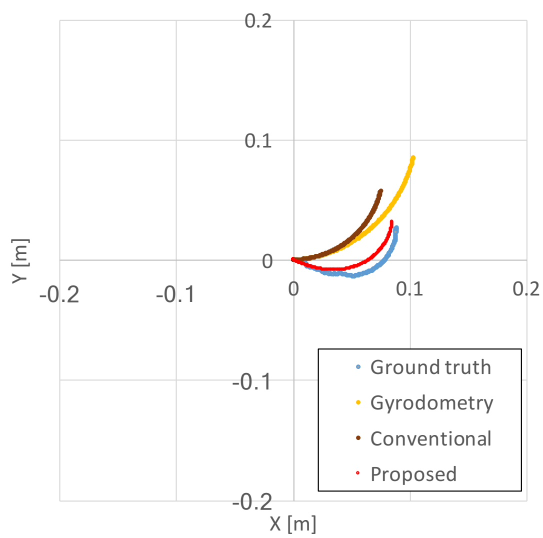

Fig. 6B *Estimated position for a tilt angle of 15 degrees and a target angular velocity of 30 deg/s.*

Fig. 6. *Example results of position estimations*

3. Path following control with lateral-slip compensation

In conventional path following (Iida 1991), the control law is described as a feedback system based on the displacement of the position and the orientation between the target path and current position:

$$\dot{\omega} = -\left(k_\eta \eta + k_\phi \phi + k_\omega \omega\right) \tag{9}$$

where η is the distance from the target, ϕ is the displacement of the desired angle, ω is the angular velocity of the robot, and $k_\eta,\ k_\phi,\ k_\omega$ are the respective control gains. In the case of following a circular path, each quantity is described as shown in Figure 7. If the robot slips longitudinally or laterally, owing to the feedback system, the control law attempts to return to the target path after the displacement is detected. The control law might therefore fail to follow the path in the case of large slippage on, for example, a weak slope. In the present study, targeting circular path following on a weak slope, we use slip angle β, which can be estimated using the method proposed in Section 2.3, as a feed-forward term of the orientation angle:

$$\dot{\omega} = -\left(k_\eta \eta + k_\phi(\phi - \beta) + k_\omega \omega\right) \quad 10$$

The aim of the proposed control law is that the robot moves to maintain an orientation error equal to the slip angle on the target path.

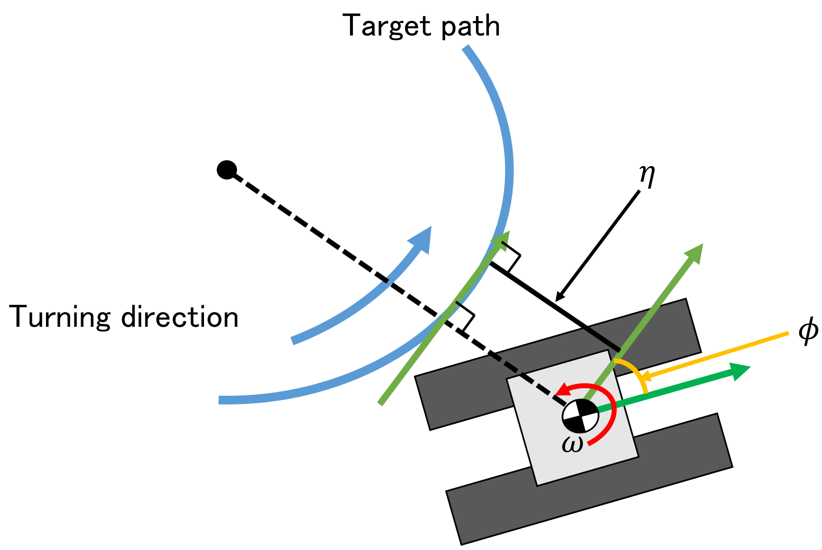

Fig. 7. Circular path following control of a skid-steering tracked vehicle.

3.1 Experiment and results

We compared the proposed control law with the conventional method in circular path following experiments. The conventional method is traditional path following (described by Eq. 9) that exploits gyrodometry (Borenstein 1996) as a position reference. The experimental setup was described in Section 2.4. In this experiment, the tilt angle of the slope was set to 15 degrees, the radius of the target circular path was set to 0.25 m, and the target velocity was fixed at 5 cm/s. The experiment was conducted three times for each control law. The gains were set to the same values for the two control laws, as determined on a solid floor in advance.

Similar results were obtained for the two control laws. Figure 8 shows an example of the trajectories of the robot's movement on the slope. In the case of the conventional method (Fig. 8A), the position estimated by gyrodometry traced the target trajectory, but the travel trajectory (ground truth) was a distance from the target trajectory. The error between the target and travel trajectory was 9.1 cm on average. Meanwhile, the travel trajectory determined by the proposed method (Fig. 8B) deviated from the target near the start point as described in Section 2.4. Afterward, the error decreased and the error was finally 1.3 cm on average. The improvement in the root-mean-square error was about 60% compared with the conventional method.

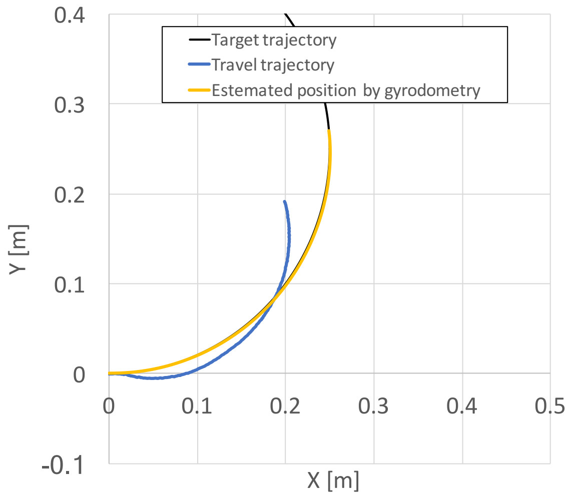

***Fig. 8A** Estimated position and path following trajectory with conventional method*

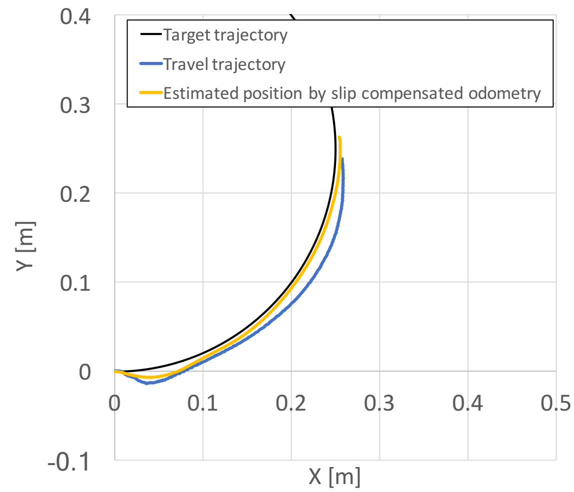

***Fig. 8B** Estimated position and path following trajectory with proposed method*

Fig. 8 Example results of trajectories. The black line is the target trajectory (having a radius of 0.25 m), the yellow line is the estimated position by each method, and the blue line is the travel trajectory archived by motion capture camera.

4. Conclusion

We proposed slip-compensated odometry based on the slip estimation method of tracked vehicles to improve the accuracy of position estimation. The slip-ratio estimation was verified that the conventional method using internal sensors can be adopted on a loose slope. The slip angle was estimated by regression analysis using a data set of positions and orientations. Experimental results show that the proposed method produces better results than established methods. We also proposed path following control considering lateral slippage. Using the estimation of the slip angle, we modified conventional control laws for path following, and confirmed good performance in a circular rotation experiment.

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