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Improvement of the Odometry Accuracy of a Crawler Vehicle with Consideration of Slippage

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Abstract— Crawler mechanisms have the advantage of stable navigation on uneven terrain; as a result, such mechanisms have been adopted for many types of locomotion of outdoor robots, including "search and rescue robots". However, crawler mechanisms always slip when tracking curved paths, and it generates a large accumulating positioning error in vehicles as opposed to conventional wheeled mobile robots. To measure the velocity of the vehicle correctly and improve the accuracy of the odometry, consideration of crawlers' slippage is very important. In this research, we propose a more accurate odometry method for crawler vehicles. In the proposed method, the vehicle can estimate the slip ratios using information from encoders (attached to the actuators) and gyro-sensors. The validity of the method was confirmed by experiments using our crawler vehicle.

I. Introduction

Crawler mechanisms offer large advantages for the locomotion of vehicles because of their large contact area, which allows them to adapt to bumpy grounds. Therefore, such mechanisms are used in many robotic vehicles for "search and rescue" applications in disaster areas, such as collapsed buildings, underground stairs, or wide cracks in the ground.

Our research group also uses crawler vehicles as research platforms of remote control for search and rescue applications. In this research, we aim to realize multi-vehicle control from a distant location with low-bandwidth communication. In this case, it is impossible to realize a conventional vision-based remote control (in which an operator controls a control-joystick by watching continuous vision information from a camera mounted on the vehicle), because of the low-bandwidth communication. To solve this problem, we proposed another remote control system[1] based on three-dimensional range sensor information, as follows:

step1: [vehicle side] Obtaining local 3-dimensional environmental information in the neighborhood of the vehicle (called "3D-info") and sending the information to the operator side

step2: [vehicle side] Obtaining the vehicle's position and orientation using an odometry system and sending the information to the operator side

step3: [operator side] Displaying the 3D-info on the monitor, and super-imposing the vehicle model on it using the odometry information

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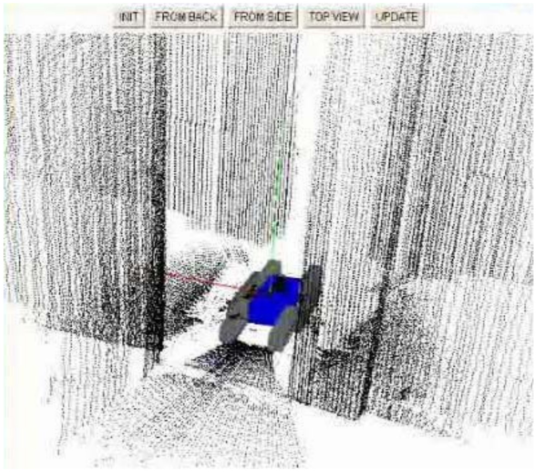

Fig. 1. GUI for remote control of crawler vehicle

step4: [operator side] Obtaining control-commands of the vehicle's actuators from a control-joystick by watching 3D-info and sending the commands to the vehicle side

step5: [vehicle side] Controlling the vehicle's actuators from the control commands from the operator

step6: Repeating the procedure from Step2 to Step5 until the vehicle approaches to the edge of the obtained 3D-info

step7: Going to Step1 for obtaining a new 3D-info

In the procedure from Step2 to Step6, the information exchanged between the vehicle and the operator is only odometry information and control commands. Therefore the above method still works under the condition of low-bandwidth communication. In Step1, the operator has to wait until 3D-info is scanned and transferred to him (usually, the size of such 3D-info data is large: in our case, it takes about 1 minute.) Figure 1 shows our GUI for the remote control of our crawler vehicle.

However, if the odometry is not reliable enough, the above method requires frequent acquisition of 3D-info, which reduces the operational efficiency and inconveniences the operator. Unfortunately, the conventional odometry method for crawler vehicle is not reliable. This is because the conventional steering system of a crawler vehicle is skid-steering and slippage between crawlers and the ground is likely to occur. To solve the above problem, we should estimate each crawler's quantitative slippage and improve the accuracy of the odometry for crawler vehicles. This is the main motivation of this research.

In related research, the analysis of slippage of wheels or crawler mechanisms goes back to 1960. Theory of Ground Vehicles"[2] is a good reference of the features of wheels and crawlers (particularly, the slip ratio and skid-steering) and is the basis of our research. Recently, regarding crawler vehicles with consideration of slippage, Shiller's group proposed a trajectory-tracking-method for crawler vehicles. They succeeded in the implementation of trajectory tracking for crawler vehicles with consideration of the dynamics in a simulation base[3]. However, their method assumes an accurate measurement of the vehicle's velocity using internal sensors (e.g., an inertial sensor), which generates an accumulated error in an actual case. To estimate slippage by external sensors directly, D.M.Helmick's group proposed a visual odometry for the Mars rover (a wheeled mobile robot) that estimates the robot's position by determining a optical-flow of the visual ground pattern[4]. This is a good approach to estimate the vehicle's position. However, it is necessary to determine the ground pattern, and the sensor system requires heavy calculations to generate visual flows.

In this research, we aim to improve the accuracy of odometry for crawler vehicles with simple sensors. We assume that the vehicle has mounted encoders to detect the velocities of crawlers and a gyro-sensor to detect the angular velocity of the vehicle's body. One of the features of our method is that the crawler's slippage is not measured directly but, rather, using both odometry information and the angular velocity of the vehicle's body. The slippage is considered in calculation of the odometry. We implemented the above method on our crawler vehicle and performed several experiments to evaluate the validity of our method.

In this paper, we introduce the proposed method in detail and discuss the validity of our method on the basis of some experimental results.

II. Odometry for crawler vehicle

A. Implementation problems of odometry for crawler vehicle

Odometry is a simple and easy method to estimate the position and orientation of mobile robots in a two-dimensional environment. However, in the case of a mobile robot that has crawlers with two diametrically opposed drives, there exists slippage between the crawlers and the ground when the vehicle tracks curved paths. Therefore, a large positioning error is generated if we simply apply the conventional odometry method to the crawler vehicle. To solve the above problem, we propose an odometry method for crawler vehicles to track curve paths which requires information of the velocities of the right crawler and the left crawler, and the angular velocity of the vehicle's body. Details are described in the following sections.

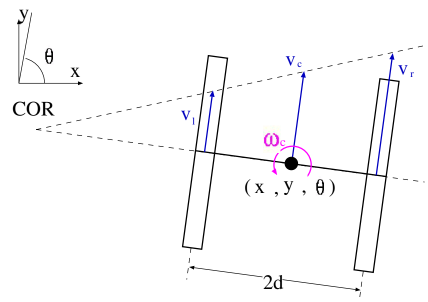

Fig. 2. Kinematic model for wheeled mobile robots

B. Kinematics for general wheeled mobile robots

The kinematic model of wheeled mobile robots with two diametrically opposed drive wheels is generally described in Fig.2. Using this model, the center position (x, y) and orientation θ of the robot are represented by

$$\dot{x} = V_c \cos\theta = \frac{v_r + v_l}{2}\cos\theta \tag{1}$$

$$\dot{y} = V_c \sin\theta = \frac{v_r + v_l}{2}\sin\theta \tag{2}$$

$$\dot{\theta} = \omega_c = \frac{v_r - v_l}{2d} \tag{3}$$

where v_l and v_r are the velocities of the left wheel and the right wheel, $2d$ is the tread, and V_c and ω_c are the linear and rotational velocities of the center of the robot.

By the time integration of $\dot{x}$, $\dot{y}$, $\dot{\theta}$ from an initial position and orientation of the robot, the robot's current position and orientation are estimated. This method is valid by assuming no slippage between the wheels and the ground.

C. Kinematics for skid-steering crawler vehicle

When the crawler vehicle tracks a curved path, estimating the slippage of both crawlers is very important to reduce the vehicle's positioning error. Therefore, we adopt a kinematic model of the odometry with consideration of the longitudinal slippage of crawlers.[2]

Let the slip ratios of the left track and the right track be a_l and a_r, respectively. These are defined as

$$a_l = \frac{v_l - v_l'}{v_l} \tag{4}$$

$$a_r = \frac{v_r - v_r'}{v_r}, \tag{5}$$

where v_l and v_r are the theoretical left and right velocities of crawlers which can be determined from the angular velocities and the radii of the pitch circles of the crawler's sprockets, the v_l' and v_r' are the the ground speed of left and right tracks. Also, let the slip angle α be the angle between the longitudinal orientation of the crawler and the actual running direction of the crawler. When a side-slip of the crawler occurs, α does not become 0.

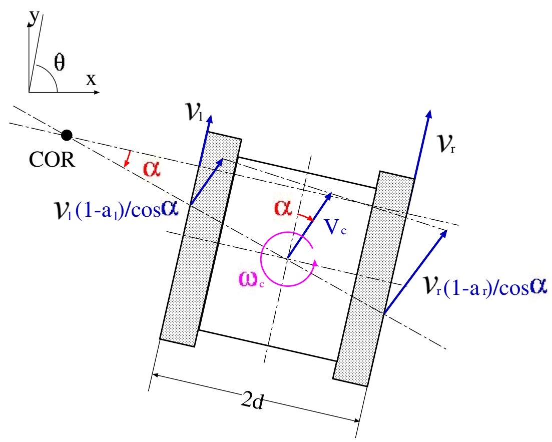

Fig. 3. Kinematic model for crawler vehicles

With consideration of the above slippage, the equation (1) – (3) can be represented by

$$\dot{x} = \frac{v_r(1-a_r)+v_l(1-a_l)}{2\cos\alpha}\cos(\theta-\alpha) \tag{6}$$

$$\dot{y} = \frac{v_r(1-a_r)+v_l(1-a_l)}{2\cos\alpha}\sin(\theta-\alpha) \tag{7}$$

$$\dot{\theta} = \frac{v_r(1-a_r)-v_l(1-a_l)}{2d} \tag{8}$$

Figure 3 shows the proposed kinematic model of a crawler vehicle. The above mathematical expansion is based on Wong's book[2].

To enable the accurate odometry of crawler vehicles, parameters (a_r, a_l, α) in equations (6)–(8) should be calculated or estimated. In this research, we assume that the vehicle's velocity is small enough and the lateral friction force is large enough. Then, it is assumed that the lateral slippage by centrifugal force is almost zero. ($\alpha = 0$)

Based on the above assumptions, the linear velocity and the angular velocity of the vehicle's body are described as

$$V_c = \frac{v_r(1-a_r)+v_l(1-a_l)}{2} \tag{9}$$

$$\omega_c = \frac{v_r(1-a_r)-v_l(1-a_l)}{2d}. \tag{10}$$

We also assume that the actual angular velocity of the vehicle $\tilde{\omega_c}$ can be directly detected by a gyro-sensor. However, it is difficult to measure parameters a_r and a_l directly. This is because both parameters relate to the balances of force and momentum between the crawlers and the ground.

At the beginning of this research, we assumed the following equation,

$$a_r = -\mathrm{sgn}(v_r \cdot v_l) a_l \tag{11}$$

where sgn(·) is a sign function. This means that (1) the value of the left-slip ratio is equal to a negative value of the right-slip ratio when the rotational directions of the left and right crawlers are the same, and (2) the value of the left-slip ratio is equal to the right-slip ratio when the rotational direction of the left and right crawlers is reversed. This situation can be intuitively explained as follows. In case (1), the faster crawler generates a traction force (that causes a positive slip ratio) of the body and the slower crawler (which is pulled by the body) generates a breaking force (that causes a negative slip ratio). On the other hand, in case (2), both the faster crawler and the slower crawler generate traction forces (that causes a positive slip ratio) to rotate the body.

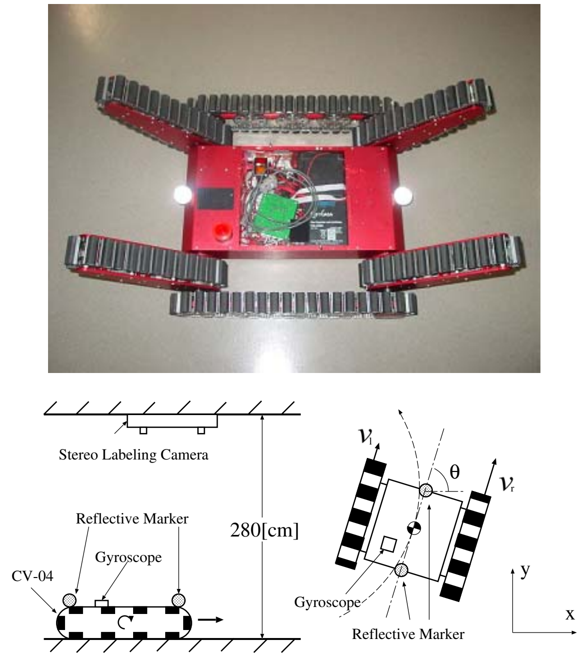

Fig. 4. Crawler vehicle used in the experiments (upper) and our experimental setup (lower)

By applying the above equation and $\omega_c = \tilde{\omega_c}$ to equation (10), we obtain the following equations:

$$a_r = \frac{v_r - v_l - 2d\tilde{\omega_c}}{v_r + \mathrm{sgn}(v_r \cdot v_l) v_l} \tag{12}$$

$$a_l = \frac{v_l - v_r + 2d\tilde{\omega_c}}{v_r + \mathrm{sgn}(v_r \cdot v_l) v_l}. \tag{13}$$

We now have the slip ratios of the left crawler and the right crawler. Once the values are assigned into

TABLE I

Specifications of the experimental setup

Crawler vehicle		Motion capture camera	
Tread	500[mm]	Fixed height	280[cm]
Length of contact area of crawler	400[mm]	Horizontal accuracy	9[mm]
Total weight	25[kg]	Frame rate	30[fps]
Distance between markers	480[mm]	Base line	400[mm]
Rate gyro's range	0–±100 [deg/sec]	Focal length	3.8[mm]

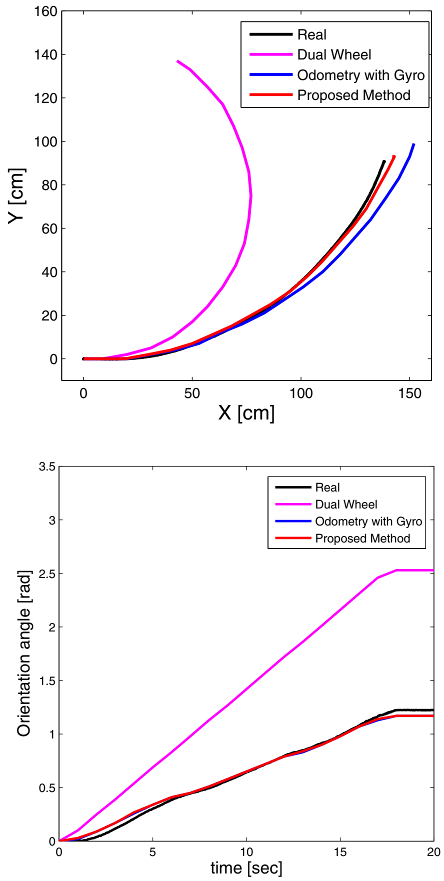

Fig. 5. Trajectory (upper) and orientation (lower) of the vehicle tracking a curve ($v_r = 15.0$[cm/sec], $v_l = 7.5$[cm/sec])

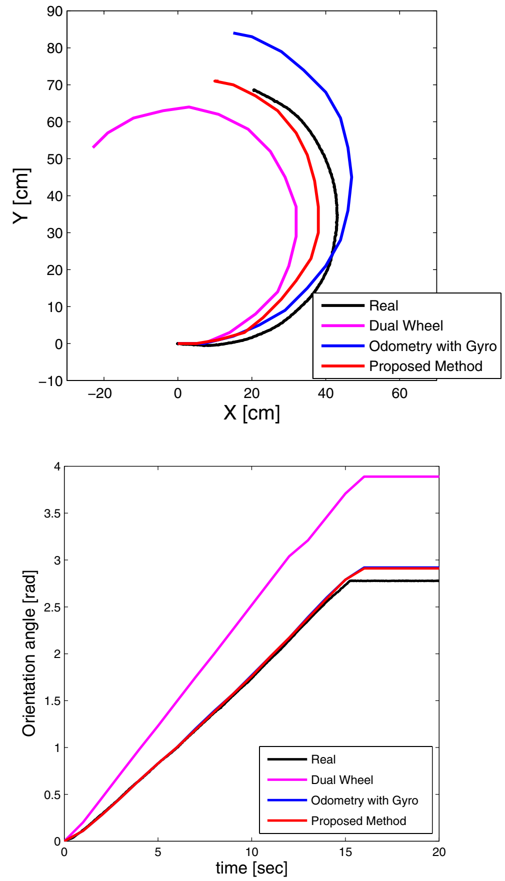

Fig. 6. Trajectory (upper) and orientation (lower) of the vehicle tracking a curve ($v_r = 15.0$[cm/sec], $v_l = 1.9$[cm/sec])

equations (9) and (10), the odometry for a crawler vehicle is performed with consideration of slippage.

III. Experiment

A. Experimental setup

To evaluate the validity of the proposed odometry system, we performed a basic experiment using an actual crawler vehicle (CV-04, Technocraft, shown in Fig.4-upper) and a motion capture camera (SLC-C02, CyVerse corp.). Figure 4 (lower) shows an overview of the experimental setup, and TABLE I shows the specifications of the experimental setup.

The vehicle has mounted encoders which measure the velocities of the left crawler and the right crawler and enable velocity control for each crawler. It also has a mounted Rate Gyroscope (CRS-03, Silicon Sensing Systems Japan) to detect the angular velocity of the vehicle's body. On the center line of the crawler, two markers for motion capture are mounted to measure the vehicle's position and orientation.

B. Additional implementation : Odometry with Gyro

To compare our method with other methods, we implemented not only conventional odometry but also the "Odometry with Gyro". The basic idea underlying this method is almost the same as that in conventional odometry, but a gyro sensor is used to estimate the robot's rotational velocity ω_{gyro} instead of measuring the rotation of both wheels. Therefore, the method is summarized as follows.

$$\dot{x} = V_c \cos\theta = \frac{v_r + v_l}{2}\cos\theta \tag{14}$$

$$\dot{y} = V_c \sin\theta = \frac{v_r + v_l}{2}\sin\theta \tag{15}$$

$$\dot{\theta} = \omega_{gyro} \tag{16}$$

The method works good in case that the wheels slip, because the gyro-sensor does not generate error in such case. However, the sensor has a weakness, namely, a drifting error, which generates accumulated orientation error of the robot. To take advantage of the strengths and reduce the effects of the weaknesses of "odometry with gyro," Borenstein et al. proposed "gyrodometry," which uses a gyro-sensor for odometry, in [5]. A feature of this method is that the vehicles generally rely on the odometry and only rely on the gyro data when a slip is detected.

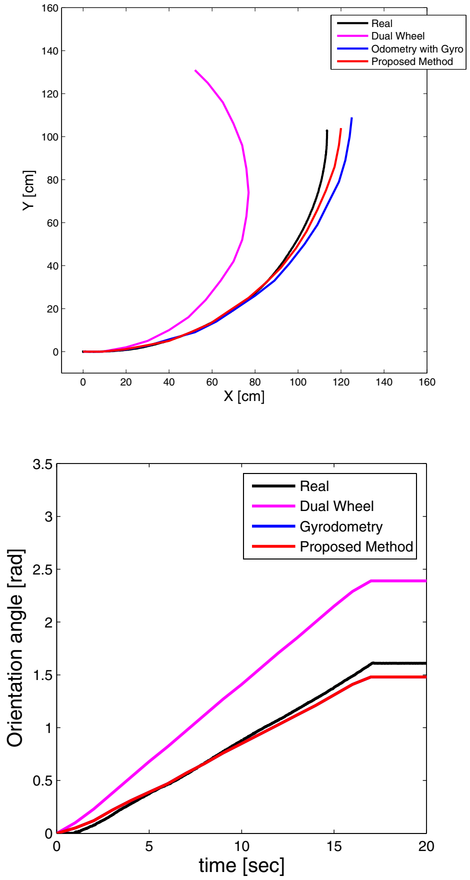

Fig. 7. Trajectory (upper) and orientation (lower) of the vehicle tracking a curve (v_r = 15.0[cm/sec], v_l = 7.5[cm/sec]) on an artificial turf

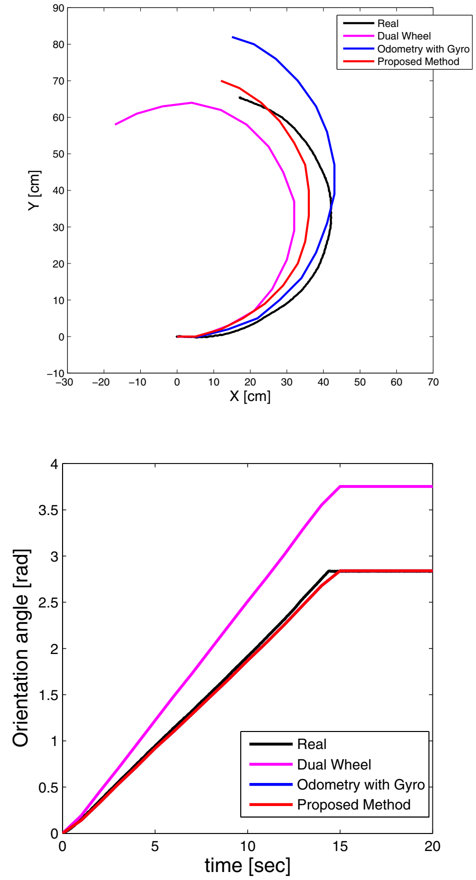

Fig. 8. Trajectory (upper) and orientation (lower) of the vehicle tracking a curve (v_r = 15.0[cm/sec], v_l = 1.9[cm/sec]) on an artificial turf

C. Experimental results of tracking a curve

We performed experiments involving a robot tracking a curve under several conditions. Figure 5 shows a typical result of a large curvature path on the p-tile, Fig.6 shows a typical result of a small curvature path on the p-tile. Figure 7 and Fig. 8 shows the same as the above paths but on artificial turf.

According to the above results and other experimental results, we confirmed that the proposed odometry method also is better than the “Odometry with Gyro” method and has a large advantage over conventional odometry. However, there still exists a positioning error, and the error increases according to the difference between v_r and v_l qualitatively. Other methods are discussed in the next section III-D.

D. Discussion

In this section, we discuss the reason for the positioning error which increases according to the difference between v_r and v_l qualitatively.

Firstly, we suppose that the following assumptions (in section II-C) may exert an influence upon the positioning error.

- Assumption of $\alpha = 0$
- Assumption of $a_r = -\mathrm{sgn}(v_r \cdot v_l) a_l$

If the former assumption is not valid, a side-slip is generated because of centrifugal force. However, we never observed a side-slip in our experiments. Furthermore, it does not result in an error in orientation, which is more important in practical cases. Now, we concluded that the latter assumption did not fit an actual situation when the difference between v_r and v_l became large.

According to Wong's book[2], the slip ratios (a_r and a_l) can be estimated by the torque of both crawlers, as follows.

Generally, when two objects are rubbed while staying in contact, each contact surface generates friction force, as shown in the following equation.

$$\tau = \mu\sigma \tag{17}$$

However, if the object's surface is soft enough (such as rubber tires or soft ground), it is difficult to model shear stress by use of the Coulomb friction model because the object's shape is changed. In such a case, the following

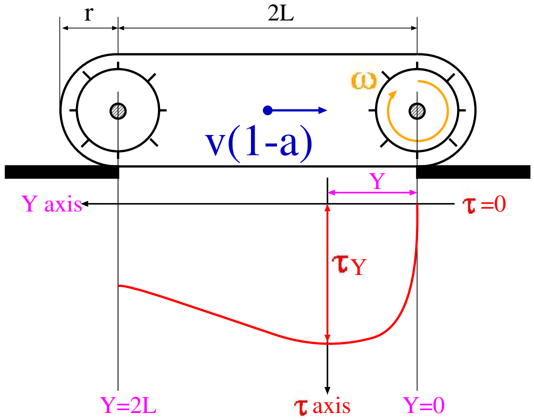

Fig. 9. A shear-distribution model of a single-track unit

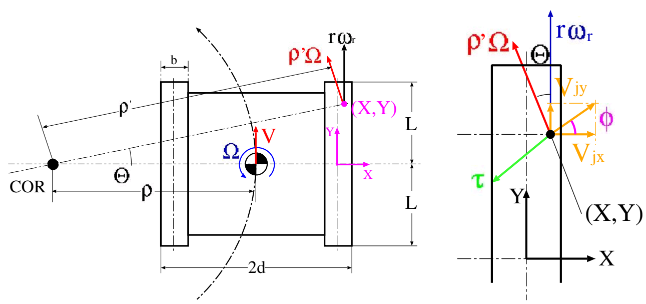

Fig. 10. A skid-steering-motion model of a dual-crawler robot

empirical formula can be used,

$$\tau = \mu\sigma(1 - e^{-\frac{j}{K}}), \quad (18)$$

where j is the shear displacement and K is the shear deformation modulus. According to the equation 18, a longitudinal shear-distribution of a single-track unit is illustrated as shown in the Fig.9.

When the normal load under the crawler is assumed to be distributed homogeneously, the relationship between the traction force and slip ratio for one crawler is obtained as follows.

$$\begin{aligned} f &= b\int_0^{2L} \tau dY \\ &= b\int_0^{2L} \mu\sigma(1 - e^{-\frac{aY}{K}})dY \end{aligned} \quad (19)$$

Figure 10 shows a skid-steering-motion model of a dual-crawler robot on a plane (which is deducted from the equation 19), and the traction force of the left wheel and the traction force of the right wheel are calculated as follows.

$$\begin{aligned} f_l &= \frac{\mu mg}{4L}\int_{-L}^{L}\left(1 - \exp\left(\frac{Y-L}{r\omega_l K}\sqrt{Y^2\Omega^2 + a_l^2 r^2\omega_l^2}\right)\right) \\ &\cdot \frac{a_l r\omega_l}{\sqrt{Y^2\Omega^2 + a_l^2 r^2\omega_l^2}}dY \end{aligned} \quad (20)$$

$$\begin{aligned} f_r &= \frac{\mu mg}{4L}\int_{-L}^{L}\left(1 - \exp\left(\frac{Y-L}{r\omega_r K}\sqrt{Y^2\Omega^2 + a_r^2 r^2\omega_r^2}\right)\right) \\ &\cdot \frac{a_r r\omega_r}{\sqrt{Y^2\Omega^2 + a_r^2 r^2\omega_r^2}}dY \end{aligned} \quad (21)$$

The above equations are the relationship between the traction force and slip ratio of each crawler in case of a skid-steering motion. Thus, in principle, if the coefficient of friction μ and shear deformation modulus K are known (or measured correctly), both slip ratios a_l and a_r should be obtained by equations 20 and 21. However, these equations include integral computation, so it is impossible to calculate a_l and a_r from f_r and f_l directly by an analytic solution. Therefore, there is a need to devise calculations that obtain a_l and a_r with a numerical solution technique or construct the table showing the relationship between the traction forces and slip ratios in advance.

IV. Conclusion

In this paper, we present a more accurate odometry method using simple sensors (e.g., encoders to detect the velocities of crawlers and a gyro-sensor to detect the angular velocity of the crawler vehicle's body). In our experience through this research, the longitudinal slippage of the crawlers is dominant, and the slippage is estimated by measuring the angular velocity of the vehicle. The validity of the above method was confirmed using an actual crawler vehicle. However, when the velocity difference between the left crawler and the right crawler became large, the proposed odometry failed to estimate the vehicle's position correctly.

Our current implementation still includes positioning error, which may be improved by detection of the crawlers' force, as mentioned in the section III-D. Therefore, our next research will attempt to confirm the above discussion as soon as possible. Our future work will expand the above odometry topics on a slope and bumpy surfaces.

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