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Force Distribution Estimation of Wheeled Mobile Robot: Application to Friction Coefficients Estimation

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Abstract: Unevenness of rough terrain causes mobile robots to be in the various wheel contact conditions so that the normal force of each wheel is affected by not only vehicle states but also geometry of terrains. For this reason, it is difficult to predict traversability of a mobile robot and maximum friction coefficients while these are key information of unmanned robot companion application. Here, we present a normal force estimation method that uses static equilibrium relation of rough terrain vehicle. The method obtains least-squares solution of static equation formulated with variables from robot configuration and contact angle, and traction force. The method is validated through simulations that show a good agreement of the estimated normal force with the real one. Finally, we present the application where the proposed method is essential.

1. INTRODUCTION

Many researches have been devoted to autonomous navigation of mobile robot since the mobile robot can be an alternative to human being in dangerous operations and unknown environment explorations. Considering the fact that the primary object of these robots is to reach operation area, one can find out mobile robots must plan the path to the area and traverse rough terrain with their position localized. In this respect, researches on the exploration of unknown environment focused on obstacle negotiation, path planning, map building, and localization of robot position. With the aid of the traversability analysis, a planned path could be optimal and more effective, because the traversability allows us to determine the risk associated with the getting stuck during traversal and predict whether the mobile robot can traverse the planned path.

Wheel-terrain interaction plays a critical role in rough-terrain mobility(Bekker, 1956 and Wong, 1976).Most of studies on traversability analysis are started from terrains characterization and classification. To assess the terrain characteristics, Gennery computed smoothed height, slope, and roughness from three-dimensional data such as that from a stereo vision system. (Gennery, 1999) Similarly, the algorithm with vision system and neural networks can determine multiple terrain characteristics that strongly affect its traversability(Howard, 2001). The limitation of a vision-based system is high sensitivity to light variation. Another approach is vibration-based method that can complement visual classification, because vibration sensed during a traverse is insensitive to lighting variation (Brooks, 2005). Beyond terrain characterization and classification, more quantitative physical property is required to predict the go/nogo of mobile robots. Maximum friction coefficient can be a candidate of this property and a part of traversability prediction.

This paper describes an estimation method of force distribution for mobile robot. The force distribution is key information not only in the maximum friction estimation but also in traversability prediction. This approach does not require force sensors and predicts traction force and normal force from kinematics and static relation of mobile robot. It obtains least-square solution of static equation that should be derived from robot kinematics. In this manner, the complex linkage mechanism plays a role of sensor for normal force. The proposed method can be used as a part of terrain friction coefficient estimation. Simulation results are presented for a six-wheeled mobile robot and show a good agreement of the estimated normal force with the real one.

2. TEST ROBOT: ROBHAZ-6WHEEL

ROBHAZ-6WHEEL (Robot for Hazardous Environment), which is designed based upon passivity and adaptability to uneven terrain, is used as a test bed. Fig. 1 shows ROBHAZ-6WHEEL. It has 6 motorized wheels connected by a passive 4-bar linkage mechanism that allows extensive adaptability to rough terrain. ROBHAZ-6WHEEL has eight DOFs: six

DOFs for the robot body and two DOFs for the right and left sides of the passive linkage mechanism.

The robot is comprised of three main parts: the driving wheel assembly, the passive linkage mechanism, and the robot body. A 50 Watt Maxon EC flat motor, 500 pulse USDigital optical encoders, and 80:1 HarmonicDrive® harmonic gears are assembled inside the wheel to afford a compact driving unit. The passive mechanism is composed of a four bar linkage and a limited pin joint. The pin joint confines the working range of the four bar linkage mechanism so as to avoid overturning. The parameters of the linkage mechanism are optimized for adaptation to the shape of the target stairs. An electrical subsystem in the main body consists of a single board computer (SBC), a controller area network (CAN) module, a wireless LAN, a motor controller, and batteries.

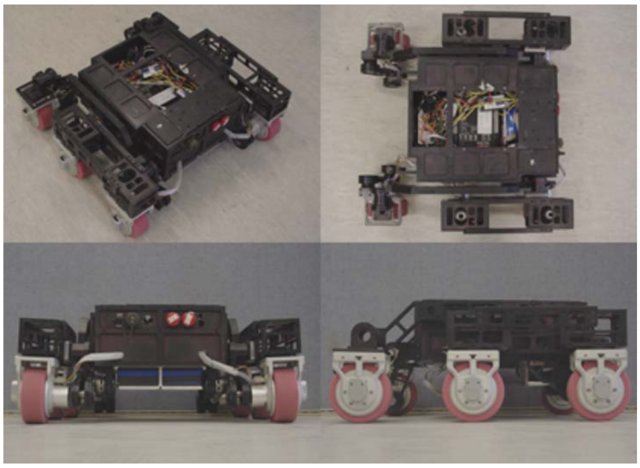

Fig. 1. Testbed: ROBHAZ-6WHEEL

The robot has a symmetrical structure. The configuration of the right and left sides of the proposed linkage mechanism is independently determined according to the environment. By using the linkage mechanism, the wheelbases between the wheels and the positions of the wheel axes relative to the gravity center of the robot body can be altered.

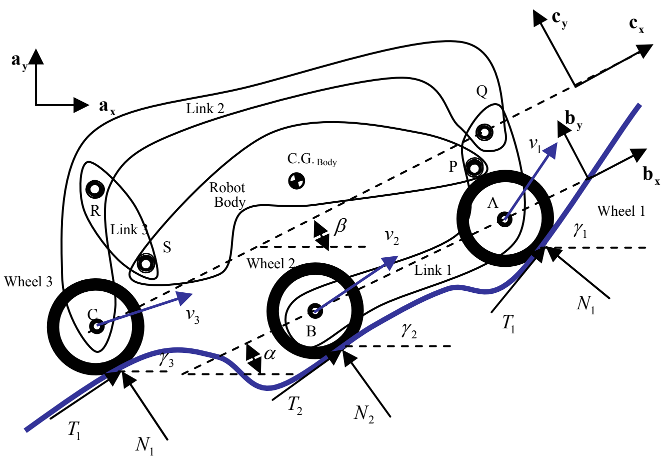

Fig. 2. Passive 4-bar linkage mechanism of ROBHAZ-6WHEEL

3. FORCE DISTRIBUTION ESTIMATION

With the relation of traction force and normal force on wheels, we can expect the minimum ratio of the traction force to the normal force in order to maintain the force balance of a robot. Here, we adopt μ_n which is defined in the equation, $T = \mu_n N$, and similar to a friction coefficient (Lamon, 2005). T and N are the traction force and normal force respectively. This adaptation is reasonable since the maximum traction force a terrain can bear increases with increasing normal force (Bekker 1969; Wong 2001). Estimation of μ_n and N allow a robot to recognize μ_n and proper force distribution state in order to avoid wheel slip. In this section, we introduce how to estimate the normal force of wheels based on static equilibrium relation.

3.1 Estimation strategy

Force distribution equation for general tree-structured mobile robot has been addressed in previous work (Hung, Orin, and Waldron 1999). Thought the test robot, ROBHAZ-6WHEEL, is not tree-structure, static force equation can be written in general matrix form as

$$\mathbf{Gx} = \mathbf{F} \tag{1}$$

,where $\mathbf{G}$ and $\mathbf{F}$ are function of robot posture, wheel-terrain contact angle and $\mathbf{x} = [T_1\, N_1 \ldots T_n\, N_n]^T$. (1) can be reduced to be expressed only with the variables of interest since we have no interest in implicitly calculating the internal forces of the system. This reduction provides benefit of computation. With known robot state parameters and the contact angle, $\mathbf{G}$ and $\mathbf{F}$ can be calculated. However, $\mathbf{x}$ is not known because the reduced from of (1) is still an underconstraint problem. In order to make the problem solvable, we estimated traction force of each wheel.

3.2 Contact angle estimation

To establish the force balance equation, wheel-terrain contact angle must be known. Iagnemma and Dubowsky proposed a method for estimating wheel-ground contact angle using commonly available sensors (Iagnemma and Dubowsky, 2004). And contact angle also can be estimated by installing multi-axis force sensors at each wheel (Sreenivasan, 1994). In this paper, we assumed that contact angles are known.

3.3 Traction force estimation

Traction force of wheels is included in $\mathbf{x}$ of (1). In order to make static force equation overdetermined. Traction force should be known. Fortunately, equation of motion for a single wheel is independent to the reaction force of a wheel axle.

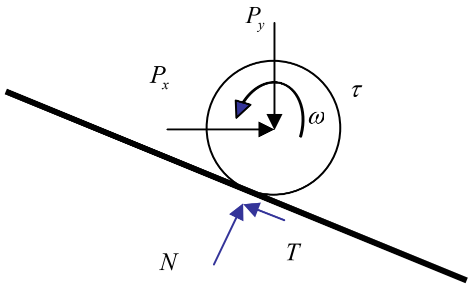

Fig. 3. Simple model of single wheel

From the model in Fig.3, one can derive the differential equation of motion as follow

$$J\dot{\omega} = \tau - rT - B\omega\,, \qquad T < \mu_s N \tag{2}$$

, where J is the moment of inertia of wheel, T is the traction force, B is the internal damping coefficient of wheel modules, r is the radius of the wheel, and μ_s is the maximum friction coefficient.

Because state space form of (2) is observable, the state variable can be observed as follow (Ohnishi, 1993)

$$\hat{T} = \frac{\omega_c}{r(s+\omega_c)}[\tau - (Js+B)\omega] \tag{3}$$

, where $\hat{T}$ is the estimated traction force, ω_c is the pole of observer.

3.4 Static Equilibrium Analysis

This section explains the static equilibrium analysis of the ROBHAZ-6WHEEL. This can be done by the static force balance. To analyze the static equilibrium, let's consider a 2-D model of ROBHAZ-6WHEEL as shown in Fig.2. It's assumed that each wheel is contacted on the terrain with just one point. This assumption is used generally in the area of mobile robot researches.

2-D model of ROBHAZ-6WHEEL consists of 4 bars (Link1~3, body). Pivots (P, Q, R, S) are the points on which each bar is connected with each other. Because of 2-D model analysis, there are 2 components of the forces acting on each pivot. And friction force and normal force are acting on the each wheel-terrain contact point. Therefore the total number of unknown forces is 14. And, in each link, 3 equations can be derived by the quasi-static force balance and the 12 equations are formulated. These neglect the robot's inertia effect because ROBHAZ-6WHEEL moves in low speed. These equations are written in general matrix form such as Eq. (1). In this case, $\mathbf{G}(14\times 12)$ is a function of mobile robot's kinematical information and wheel-terrain contact angles. And $\mathbf{x}(14\times 1)$, $\mathbf{F}(14\times 1)$ are unknown vector and gravity force acting on the robot respectively.

(1) is very hard to solve in real-time because of its heavy form. In general this form can't be reduced. When $\mathbf{G}$ has the special form such as (4) which can decouple the matrix, the matrix size can easily be reduced. And then, simplified form can enable to diminish the computational burden. This decoupling is always possible if a robot has a linkage chain which is not directly connected with wheels in the parallel loop. In this case, six equations of link3 and body can be decoupled and the reaction force at pivot P, S ,and Q are calculated only with given Q and R position.

$$\mathbf{G} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{0} & \mathbf{C} \end{bmatrix} \tag{4}$$

,where $\mathbf{C}(6\times 6)$ is a square matrix.

Let $\mathbf{x} = [\mathbf{x_c} \quad \mathbf{x_u}]^T$, $\mathbf{F} = [\mathbf{F_c} \quad \mathbf{F_u}]^T$, (1) can be written in decoupled form such as (5) and (6).

$$\mathbf{A}\mathbf{x_c} + \mathbf{B}\mathbf{x_u} = \mathbf{F_c} \tag{5}$$

$$\mathbf{C}\mathbf{x_u} = \mathbf{F_u} \tag{6}$$

where $\mathbf{F_c}(8\times 1)$, $\mathbf{F_u}(6\times 1)$, $\mathbf{x_c} = [T_1\, N_1\, T_2\, N_2\, T_3\, N_3\, Q_x\, Q_y]^T$, and $\mathbf{x_u} = [P_x\, P_y\, R_x\, R_y\, S_x\, S_y\,]^T$ are gravity force vectors and the decoupled force vector respectively. By solving (6), $\mathbf{x_u}$ can be obtained and the system's unknowns can be reduced as (total system's unknowns - the number of $\mathbf{x_u}$'s order) In 2-D ROBHAZ-6WHEEL, (1) can be formulated by the reduced form as shown in (7).

$$\mathbf{A}\mathbf{x_c} = \mathbf{F_c} - \mathbf{B}\mathbf{C}^{-1}\mathbf{F_u} \tag{7}$$

Eliminating Q_x, Q_y from equation (7) with extra algebraic manipulation yields

$$\mathbf{H}\mathbf{x}' = \mathbf{F}' \tag{8}$$

,where $\mathbf{H}(4\times 6)$, $\mathbf{F}'(4\times 1)$ are reduced form of the known matrix and vector, $\mathbf{x}'(6\times 1)$ is an unknown vector whose components are wheels' friction forces and normal forces we are concerning.

A problem such as (8) is still an underdetermined problem whose redundancy is 2. Therefore, there are infinite numbers of solution which mean infinite sets of force distribution in order to maintain the static force balance. The same phenomenon can be found in a bicycle that stopped in the slope. We can make a bicycle stop by operating the front brake of the rear brake and the both. If 3 wheels' traction forces are known, (8) can be converted to an over-determined problem. This overdetermined problem can be solved using the least-square method.

4. SIMULATIONS AND EXPERIMENTAL RESULTS

Simulations have been performed in order to verify the proposed estimation methods. Using ADAMS, dynamic simulation parameters have been set as close as possible to correspond with a real mobile robot.

Fig. 4. Simulation environment

All the geometric dimensions, mass, and inertia parameters are imported from a 3-D CAD program. Thus, these parameters can be accurately calculated from the geometry and density information of the 3-D CAD program, including the battery, single board computer, DC-DC converter, and etc. Internal damping torque of the wheel proportional to the angular velocity has been implemented from a parameter identification process. The impact and friction between interfacing surfaces are modeled as follows (Goldsmith 1960; Lankarani and Nikravesh 1994):

$$N = k_c g^n + c\frac{dg}{dt} \quad for\ g \geq 0 \tag{10}$$

$$T = \mu N \tag{11}$$

,where k_c is the stiffness of contacts, g represents the penetration of geometry into another, n is a real positive value denoting the force exponent, c is a damping coefficient of contacts, dg/dt is the penetration velocity at the contact points, and μ is the friction coefficient. The following parameters were used: the stiffness of contact k_c=*150N/mm*; the force exponent n = *2.1*; damping coefficient c = *20 Ns/mm*. The total mass of the robot is 28kg: weight of a body, a wheel, and linkage are 10kg, 10kg, and 8kg, respectively.

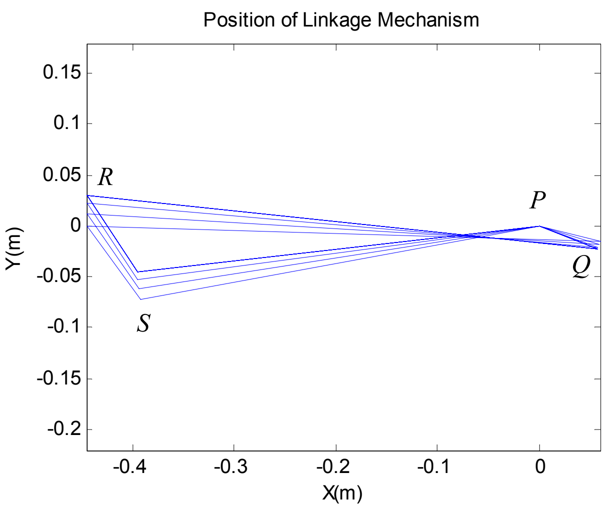

Fig. 5. Position of linkage joints

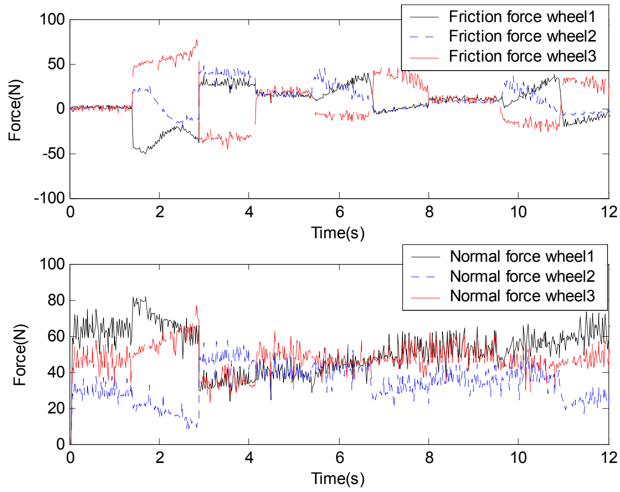

Fig. 6. Force distribution measured from simulation model

Figure 4 shows the simulation environment. All of wheels are controlled to rotate with constant angular velocity. Relatively smooth geometric profile is selected as a test environment because successive change of contact angle can provide the sudden change of force distribution as shown in Fig. 6. Thus we can observe how fast the proposed method responses. Rate gyroscope and inclinometer are installed in link1 and link2 in Fig.2 in order to calculate the position of linkage position. Figure 5 shows the position analysis of 4-bar linkage in the robot properly performed.

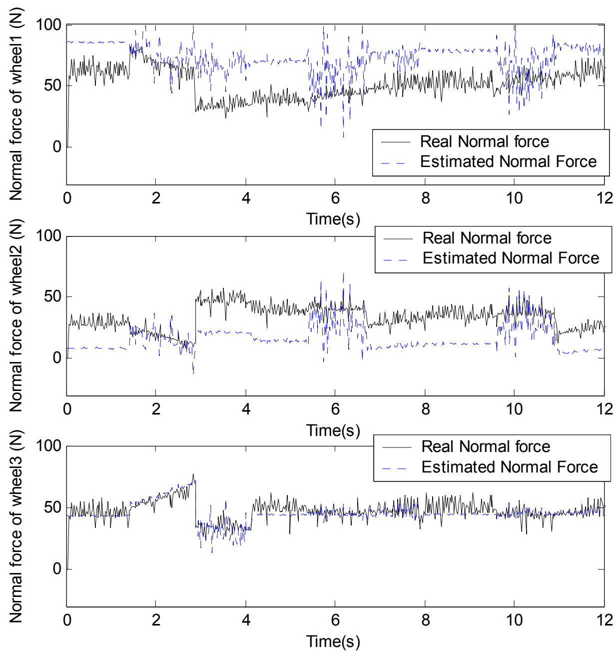

Fig. 7. Estimated normal force with linkage mass lumped to body (body: 9.5kg, wheel:1.5kg)

Exact force distribution is obtained from ADAMS model as shown in Fig. 6. Then, we applied the proposed estimation method to the test robot. The important thing that should be addressed here is mass of linkage. Though we have not considered the mass of linkages in derivation of static force balance equation, real test robot has then and the simulation model also includes mass property of linkages. Thus, two set of estimation have been conducted. In the first set, we assume that mass of linkage is concentrated in the mass center of the body and the second, in the wheels evenly.

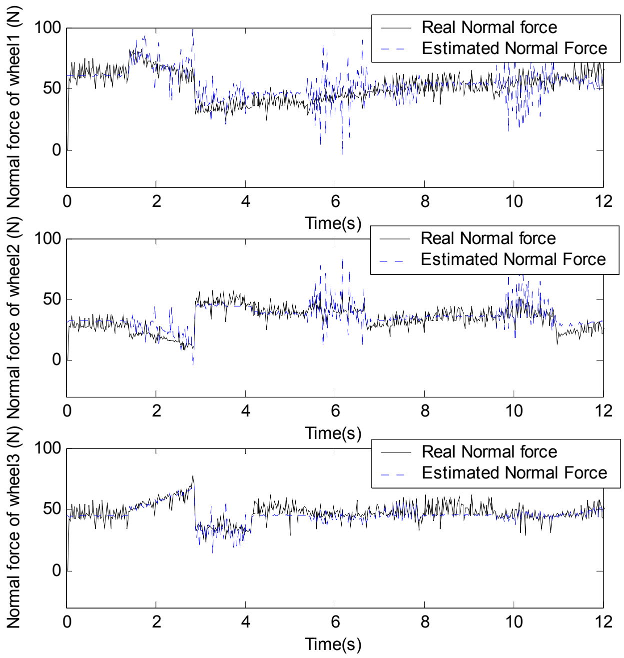

Fig. 8. . Estimated normal force with linkage mass lumped to wheels (body: 5kg, wheel:3kg)

Figure 7 and 8 shows the estimation results of normal force with the lumped mass assumptions. Better performance is observed with the second case that the mass of linkages is lumped in the wheels evenly. Mass of body was 5kg and wheels, 3kg. These results are reasonable because the relatively heavy linkages are connected to wheels and push the wheel module to gravity direction.

5. FRICTION COEFFICIENTS ESTIMATION

In this chapter, we briefly present friction coefficient estimation. As mentioned in previous chapter, we adopted μ_n which is similar to a friction coefficient. Once we find maximum allowable μ_n avoiding slip of wheels, a robot can avoid trapped condition by slip and guarantee its safety. A robot can determine go/nogo of the specific paths with geometric information of terrain as well. From the proposed estimation method, we can estimate the traction force and the normal force. Estimation of maximum friction force is the remained work that should be done in order to identify maximum allowable μ_n.

One solution of this problem is increasing torque linearly. The rapid change of angular velocity could indicate whether the applied wheel torque is higher than the torque induced by the maximum friction force or lower than that induced by kinetic friction force. In the further work, the wheel torque will linearly increases until the controller observes specific angular acceleration, which indicates that the applied torque is higher than the torque induced by the maximum friction force.

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