Motion Dynamic Simulations and Experiments of an Exploration Rover on Natural Terrain

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Abstract

This paper investigates a physical model of the wheel traction in the relationship of the motion dynamics, and thereby studies the cases where a rover negotiates with natural rough terrain, slips and stacks on a steep slope. Experiments are carried out with a rover test bed to observe the physical phenomena and extract essential parameters, and the dynamic simulations are carried out to be compared with the experimental data. Illustrative simulations show that the motion of the vehicle, including the adaptive response of the rocker-bogie suspension to rough terrain and the development of the slip on a sandy slope, is successfully modeled and simulated with the in-house software dedicated for dynamics simulation.

1. Introduction

The advantage of a surface locomotion rover in planetary exploration has been proven by NASA’s Pathfinder mission in 1997 [1]. NASA recently announced its 2003 Mars Exploration Program will include a couple of rovers in a larger scale with much longer traveling distance and more challenging terrain comparing with those of the Pathfinder rover[2]. In Japan, exploration rovers are discussed under the NASDA/ISAS joint mission to Moon, named SELENE [3].

Corresponding to such growing attention and technology requirements, there are an increasing number of research papers on exploration rovers being published. The research area is very broad from mission design and analysis [4][5], rover designs [6][7][8], sensing and navigation, obstacle avoidance, traversal and path planning [9], motion kinematics and slip model [10], to field tests [11][12], and so on. However, very few papers deal with motion dynamics based control. This is because the rovers are so far considered to move very slowly to experience dynamic effect, and also the dynamic analysis seems complicated requiring sophisticated models of tire-soil traction mechanics and the body-suspension-wheel dynamics. But recently, some papers report advantage of physics based motion control that involves a model of traction mechanics with quasi-static force distribution [13][14][15].

The approaches in this direction deal with the wheel-soil contact angle, which makes influence on the force distribution tangent and normal to the surface at the contact point [10][13]. However, it is considered more essential to discuss the ratio of the tangent and normal forces, that involves the traction force as a function of the slip ratio at each dynamic situation, in addition to the static projection of the gravity force by the contact angle.

The goal of this research is to establish a model to appropriately evaluate the traction force ratio in the relationship of the motion dynamics, and thereby derive a traction control law to maximize the efficiency and to avoid a critical trap or stack. As an initial step, the experiments are carried out to observe the physical phenomena and extract essential parameters, and the dynamic simulations are developed to be compared with the experimental data.

This paper is organized as follows. In section 2, the rover test bed with 6 wheels connected by a Rocker-Bogie type suspension link is introduced. In section 3, the experimental data obtained with the test bed on dry sand are presented, and the profile of the tire slip is characterized. In section
Figure 1: The rover test bed (side view and front view)

Figure 2: The rover test bed moving on rocky rough terrain

4, driving force for the rover dynamics simulation is assumed as a function of the slip ratio. In section 5, the motion dynamics of an articulated rover is formulated for extensive simulations, then in Section 6, an illustrative result of the simulation is presented. In the last two sections the motion of the vehicle, including the adaptive response of the rocker-bogie suspension to rough terrain, is successfully modeled and simulated with the in-house software dynamics simulator, the SpaceDyn[16]

2. Rover Test Bed

The rover test bed developed at Tohoku University has the dimension in the envelope of 350mm cube, weighs 8.0 kg in total (Figures 1 and 2.) It has 6 wheels connected by a Rocker-Bogie type link system. The wheelbase distances both front to middle and middle to rear are 130mm. The tread distance of the right and left wheels is about 300mm. Each wheel, which is originally for radio-controlled toys and covered by soft rubber with small rubber spikes, has the diameter of 90mm. Front and rear wheels have active steering DOF. Our Rocker-Bogie suspension uses parallel links unlike that is used in the Pathfinder rover or other NASA’s Mars rover prototypes. In the main body, there mounted a Linux based computer system with a 233MHz K6 cpu (Figure 3) that communicates with a Windows based computer for operation controller by wireless Ethernet link. Also mounted a H8 processor based PWM motor controller, an independent data logging system, and a battery and power supply unit.

The control and measurement system block diagram is depicted in Figure 4. In the experiments presented in the following section, an open loop control for wheel velocities is performed along the remotely commanded duty ratio for each PWM driver. The state of the rover is monitored by the following on-board sensors: each tachogenerator for 6 wheels, each potentiometer for 4 steering axes, total 4 potentiometers for the Rocker-Bogie link state measurement (right and left rockers, right and left bogies.) These analog values are digitized and recorded by an independent compact data logging system (Keyence NR-2000.)

Note here that the right and left rocker links are connected so that these two links moves in a sym-
metric way, like the Pathfinder rover, therefore the above measurement is redundant. Note also that the rover is not equipped with an attitude sensor or an inclinometer. The orientation of the body is measured by an optical 3D motion tracking system in the following experiments. For this purpose there mounted four color cue markers on the top of the base body.

3. Experiments

Experiments are carried out on uneven surface of dry sand with several rocks. In the experiments, the internal state variables such as wheel velocities and suspension link angles are measured by on-board sensors. On the other hand, the motion of the body in the inertial frame is measured by a 3D visual tracking system that uses a set of stereo cameras fixed to the experimental field (Figure 5.) A map of the sandy field (2m × 2.5m) is obtained by the 3D measurement system as Figure 6.

If more than three positions of marker are observed, position and orientation of rover’s center of gravity can be calculated. Redundancy of the marker position is used to increase the precision of these calculation. The motion trace of the rover main body, measured by the 3D camera system, is differentiated to obtain the body velocity $v_b$ in the inertial frame. The traveling velocity of each wheel $v_x$ in the inertial frame is obtained by kinematic calculation from the body velocity and the state of the suspension links. The circumference velocity of each wheel $v_w$ is measured by tachogenerator, then the slip ratio of the wheel is calculated.

Four sets of experiments are carried out in this environment (Figure 7.)

**EXP-1** Straight path locomotion from a flat area to a steep slope.

**EXP-2** Skid steering in an almost flat area.

**EXP-3** Negotiation with a single round rock which has a half diameter of the wheel.

**EXP-4** Negotiation with several round rocks scattered randomly.

In EXP-1, the rover test bed is observed to loose its body velocity when it is climbing up a slope, and then stops at a certain inclination in spite that all wheels are commanded to rotate at a constant velocity. This yields tire slip and finally, the rotating wheels dig a hole to sink themselves in the
sandy slope. It leads to a critical stack of the vehicle and difficult to get out.

An example of the data is depicted in Figure 8, in which the top is the body velocity $v_b$, the middle is one of the tire circumference velocity $v_w$, and the bottom is the corresponding slip ratio $s$. In this example, the rover test bed travels straightly climbing up a smooth but gradually increasing slope.

It is observed that the both the body velocity and the tire velocity decrease along the slope, but in different profiles. The corresponding slip ratio is changing from near zero to minus one. From $T=11$ to 23 seconds, the body seems to move on a flat floor with almost constant velocity, yielding almost zero or very small slip. After $T=23$ the slope starts and at $T=35$ seconds the body finally stops due to the excessive load, but the tire still keep rotating then yielding $s = -1$. At this moment, the corresponding tire is digging the sandy surface vertically. Such observation on the transition profile of the velocities and the slip ratio are useful to infer the tire traction model.

On the other hand, the effectiveness of the rocker-bogie suspension system for bumpy terrain is observed in EXP-4, in which the rover test bed is moving on the surface with randomly placed rocks. Figure 9 depicts the profile of the rocker and bogie angles in one of such examples. In this particular case the right side has more bumps. Note that the right and left rockers have a symmetric profile because of the differential link to connect the both. Some asymmetric feature is observed due to the back-rash of the link connection.

4. Driving Force

In this section, the modeling of the driving force is discussed, which is essential for the simulation of wheeled vehicle. The functionality of a wheel is to support on vehicle and to generate the driving force that accelerates or brakes the velocity. The driving force is caused by stiffness and friction between tire and soil. It can be modeled as a function of the slip ratio of tire, distinguished into the traction force (in the direction of the tire rotation) and the side force (in the perpendicular direction.)

In literature of vehicle dynamics [17], the slip ratio $s$ is defined as follows:

$$s_x = \begin{cases} 
\frac{(v_x - v_w)}{v_x} & (v_x > v_w) \\
\frac{(v_x - v_w)}{v_w} & (v_x < v_w)
\end{cases}$$

(1)

$$s_y = \begin{cases} 
\frac{\tan \alpha}{1 - |s_x|} & (v_x > v_w) \\
|s_x| \tan \alpha & (v_x < v_w)
\end{cases}$$

(2)

where $v_x$ is tire traveling velocity, $v_w$ is circumference velocity, and $\alpha$ is slip angle. The direction $x$ and $y$ (used as a suffix) are defined as shown in Figure 10.

In general, $s$ is positive when the vehicle is braking, on the other hand, negative when accelerating.

Here, the tire traction force $f_t$ is assumed as a function of the slip ratio $s$ in such way as:

$$f_t = f_n \cdot f(s)$$

(3)

where $f(s)$ is the load-traction factor, taking a value between -1 and 1, and $f_n$ is the force (load) in the normal direction of the surface where the tire
In this paper, we consider both the elasticity and viscosity of tire, then the model is generally expressed as:

\[ f_n = Cz(h)^r + Dz(h)^s \]  

where \( h \) is the sinkage of the tire. (see Figure 11)

Modeling of the traction factor as a relationship of the slip ratio is one of the most important point in traction mechanics. There are a number of literatures in the field of automobile engineering and terra-mechanics that makes detailed analysis of tire mechanics. But some models include variables and parameters that are difficult to measure in practice. Even force-torque sensors, they are difficult to build in a motor driving shaft or a suspension link. Here the authors try to extract the traction factor only by velocity measurement.

The principle to obtain the traction factor as a function of the slip ratio is depicted in Figure 12. From on-board tachogenerators and the external 3D measurement system, the velocities \( v_x \) and \( v_w \) are obtained. The slip ratio \( s \) is calculated using Equation (1). The relationship between the tire circumference velocity and the slip ratio is thus obtained (the top-left graph in Figure 12.) The slip ratio is then just mapped onto the vertical axis of the bottom-right graph. On the other and, the circumference velocity can be converted to the traction force using the motor characteristics between the rotational velocity (in proportion to the circumference velocity) and the driving torque (in proportion to the traction force,) under the condition of constant input voltage to a DC motor. This relationship is known as linear with a negative slope, which is confirmed by preliminary calibration using a force/torque sensor and a tachogenerator under our experimental condition. We then obtain the relationship on the traction factor.

The experimental data obtained from EXP-1 are plotted on Figure 13 with red dots. The data plots show some diversity as a nature of physical measurement, yet its tendency is clear and can be approximated by a polynomial (black curve) using the least square method. The curve shows the function of the traction factor versus the slip ratio for the tire and sandy surface we used in our experiments. The obtained curve has an offset value at a point where the slip ratio is zero. This offset should be related to the resistance in pressing and plowing the sand.

The above knowledge is used in the following simulations.
5. Simulation

In order for better understanding of the physical phenomena and motion dynamics of the rover locomotion, the flame work for computer simulation has been developed using an in-house multipurpose simulation software called the SpaceDyn. The SpaceDyn performs forward dynamics computation based on the Newton-Euler formation for a multiple link system with multiple terminal branches, on which explicit forces are given.

In the simulation, the rover system is modeled as an articulated multibody system with a moving base. Figure 14 shows a typical example of an articulated body system. The rocker-bogie suspension system is constituted by passive links between the wheels and the base as shown in Figure 15.

The computational flow of the simulation is described as follows: Motor torque of each wheel is given as input. Current velocity of each wheel are calculated by solving the kinematics with the state variables of the rover. Slip ratio is obtained from traveling and circumference velocities with Equations (1) and (2). At each contact point between the wheel and the terrain surface, called as a terminal point in the simulation, the normal force by Equation (5) and the traction force by Equation (3) with Figure 13 are applied according to the physical state of the point. With the computation of the forward dynamics and numerical integration, the state variables of the rover at a next time step are obtained.

6. Simulation Results

Simulations are carried out to verify the characteristic behavior of the rover in two aspects. One is the adaptive motion of the rocker-bogie suspension on bumpy terrain. The other is the slip and stack on a sandy slope. Each simulation is performed to compare a corresponding experiment.

Figure 16 depicts a comparison of the rover motion moving over a bump. Here the maximum height of the bump is assumed a half of the wheel. The left column of the graphs are obtained by experiment, EXP-4, and the right are simulation. The top graphs show the Rocker link, and the bottom ones the Bogie link. In the simulation, the rover is supposed to run faster than the experiment although, the characteristic motion profile obtained by the simulation well describes the physical motion.

Figure 17 compares the experiment and simulation in the slip characteristic. The left column is from experiment, EXP-1, and the right is simulation. The bottom graphs show the slip ratio of a front wheel, and the top show the elevation of the corresponding wheel climbing up a sandy slope. In the experiment, the slip ratio profile is noisy s-
ince it is based on the velocity data obtained by the differentiation of the position and angle measurement. The simulation agrees the experiment in a general characteristics that the tire start slipping on the slope, until the slip ratio develop to reach minus one; total slip. As this point, the wheel starts digging the surface rather than traveling. The simulation model, particularly the traction factor profile, Figure 13, should be carefully improved for better representation of the characteristic profile from the slipless traction to the total slip.

7. Conclusions and Future Work

In this paper, the physics and motion dynamics of a wheeled vehicle (rover) on uneven natural terrains is studied. As an initial step, experiments are carried out to observe the physical phenomena and extract a traction model from the motion data profiles. The dynamic simulations are also developed to be compared with the experimental results. Illustrative simulation results show that the motion of the vehicle, including the adaptive response of the rocker-bogie suspension to rough terrain and the development of the slip on a sandy slope, is successfully modeled and simulated with the in-house software dynamics simulator named the SpaceDyn.

As a future research direction, a traction control law to maximize the efficiency and to avoid a critical trap or stack should be established and tested. From a careful examination of the slip profiles obtained by experiments, a critical threshold value will be suggested. If the slip ratio exceeds this value the wheel starts slipping and digging. In order to avoid this, the wheel velocity should be regulated or the load condition should be controlled.

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References

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Figure 16: Simulated rover motion moving over a bump

Figure 17: Simulated rover motion climbing up a slope