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Development of in-wheel sensor system for accurate measurement of wheel terrain interaction characteristics

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Abstract

Planetary rovers need high mobility on a rough terrain such as sandy soil, because such a terrain often impedes the rover mobility and causes significant wheel slip. Therefore, the accurate estimation of wheel soil interaction characteristics is an important issue. Recent studies related to wheel soil interaction mechanics have revealed that the classical wheel model has not adequately addressed the actual interaction characteristics observed through experiments. This article proposes an in-wheel sensor system equipped with two sensory devices on the wheel surface: force sensors that directly measure the force distribution between the wheel and soil and light sensors that accurately detect the wheel soil surface boundary line. This sensor design enables the accurate measurement of wheel terrain interaction characteristics such as wheel force distribution, wheel–soil contact angles, and wheel sinkage when the powered wheel runs on loose sand. In this article, the development of the in-wheel sensor system is introduced along with its system diagram and sensor modules. The usefulness of the in-wheel sensor system is then experimentally evaluated via a single wheel test bench. The experimental results confirm that explicit differences can be observed between the classical wheel model and practical data measured by the in-wheel sensor system.

Keywords: Wheel–soil interaction; In wheel sensor system; Force distribution

1. Introduction

Recently, mobile robots called rovers have been used for planetary exploration missions. The Mars exploration rover (MER) mission or the Mars science laboratory mission (NASA/JPL) are the most notable examples. The surface of the planetary body is covered with various size of component: from loose or hardened soil to bedrocks. The rover can detect physically-visible obstacles using its on-board cameras and avoid its collision. However, wheels of the rover may get stuck in sand: particularly in loosely covered sand. In the MER mission, one of the rovers Spirit got stuck in the sandy soil and terminated its mission. Therefore, the accurate estimation of wheel soil interaction mechanics is important.

A well-known interaction model between the wheel and soil based on the terramechanics was proposed by Bekker (1960) and Wong (1978). This model has been widely used for estimating the behavior of rover driving characteristics on various types of off-road surfaces (Gee-Clough, 1976; Rubinstein and Hitron, 2004).

This wheel–soil interaction model includes various soil parameters (Shiby et al., 2005; Bauer et al., 2005). Moreover, the classical interaction model assumes homogeneous soil and a flat terrain surface. However, the behavior of rovers in the real environment may often violate such assumptions because wheel slip or sinkage deforms terrain conditions. Off-road surfaces are also typically formed by

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complicated undulations. Therefore, it is difficult to accurately estimate the physical characteristics of wheel–terrain interaction, such as slip and sinkage. Many studies have been dedicated to validating the wheel–soil interaction model (Ishigami et al., 2006, 2009; Inotsume et al., 2013; Senatore et al., 2014; Favaedi et al., 2011). In these studies, the classical model was applied to calculate the force distribution generated at the wheel contact patch, and sinkage.

Ojeda et al. investigated terrain characterization and classification using the information obtained from a wheel motor (Lauro et al., 2005). In this study, the wheel rotational angle was measured by an encoder installed on the motor and motor torque was calculated from the motor current. While monitoring this wheel information, they validated the terrain characterization and discussed soil classification. This study had the advantage of a simple sensing system, which performed terrain characterization by only using motor torque. However, it is difficult to obtain the accurate values of motor current and torque, because the rovers used in exploration usually have small motors and large gear reduction ratio, resulting in relatively large parasitic torque.

Iagnemma et al. performed an accurate measurement of wheel characteristics based on data obtained from wheel motors and camera modules (Iagnemma et al., 2003). Associating the values of motor torque with wheel sinkage obtained by a camera mounted outside the wheel, the wheel mobility on sandy soil could be estimated. In this case, rover behavior can be estimated relatively well if the wheel drives on various off-road surfaces. However, in this study, motor torque measurement may not be stable owing to dynamic wheel behavior and the wheel sinkage obtained by image processing may often have critical errors owing to ambient light or image quality.

Nagatani et al. developed an in-wheel sensor, the surface of which was covered with several tactile force sensor arrays (Nagatani et al., 2009). Each sensor directly measured the actual force between the wheel and soil. Information obtained from the in-wheel sensor was applied for estimating soil parameters and slip ratio. However, they remarked that wheel sinkage (wheel–soil contact angles) could not be accurately determined because of a low signal-to-noise ratio of the force sensors. They also concluded that the force distribution area measured by the in-wheel sensor may be considerably smaller than the actual wheel–soil contact area. In addition, the actual phenomenon formed between the wheel and soil may be different from that estimated using the classical wheel–soil interaction model. Therefore, it is important to use a more reliable sensing principle for detecting the relationship between the wheel and soil.

In the present study, an in-wheel sensor system called advanced sensor-wheel with pressure and light detection (ASPL) was developed to overcome the above-mentioned difficulties (Fig. 1). This sensor wheel can reveal the physical interaction between the wheel and soil using the force and light sensors installed on the wheel surface.

2. Development of ASPL

2.1. System overview

The ASPL is composed of a power supply module, control module, and sensor module. The power supply module provides stable electric power for each of the other modules. The control module processes the information obtained from the force and light sensors. The force and light sensors are installed on the sensor module with an amplifier to directly measure the interaction between the wheel and soil. All of these modules are integrated within

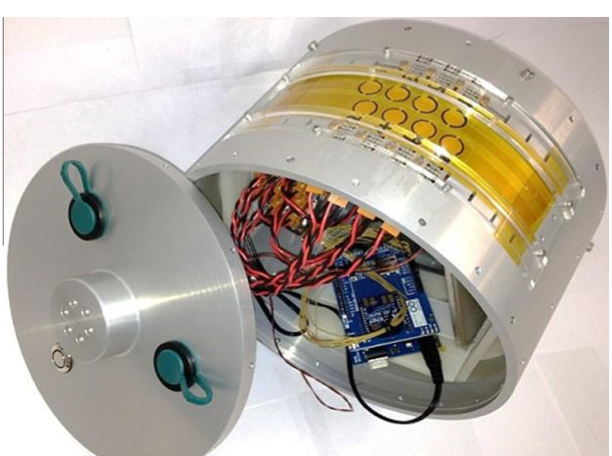

Fig. 1. Advanced sensor wheel with pressure and light detection (ASPL).

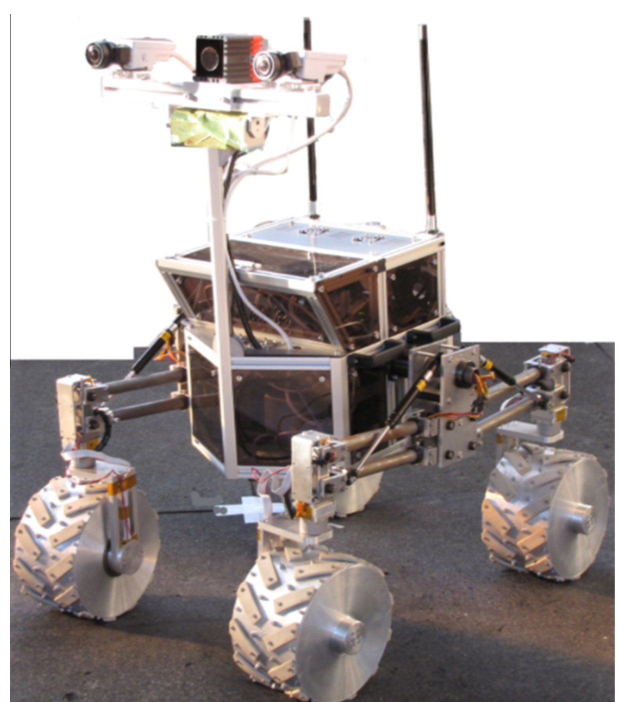

Fig. 2. Image of the rover.