Dynamics Modelling of Rovers for State Estimation

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EXTENDED ABSTRACT

Wheeled rovers play a central role in exploration tasks in unstructured environments for both terrestrial and extraterrestrial applications. State estimation without the availability of global measurements is a key requirement for the functioning of these systems. Such estimation has to rely on on-board sensors such as wheel encoders, inertial measurement units (IMUs), and vision sensors. The overall state estimation algorithm generally incorporates information from these different sensors through sensor fusion. A core challenge for the state estimation problem is the wheel slip on soft terrain. If there were no slip then wheel encoders alone could provide accurate results. We particularly investigate what best performance can be achieved using only wheel encoders. In the place of additional sensors we propose to employ a rover model that incorporates the terrain reaction forces in the estimation algorithm. In this paper we describe the modelling approach that is well suited for estimation algorithms.

A rover can generally be considered as an articulated mechanical system with a central body, the chassis. The main phenomenon that differentiates a rover, or any wheeled vehicle, from other types of mechanical systems is the interaction with the terrain through the wheels. Otherwise, if the rover is removed from the ground and only its internal mechanics is studied then it is no different from any other mechanism. Simplified models that allow for the development of closed-form analytical formulations are frequently employed as these can be easily used together with estimation/control methods.

A rover is a three-dimensional mechanical system. However, the nature of typical operations can be best captured with models that are designed to describe the specific features of the operation analyzed. The main function of a rover is to traverse terrains; its mobility and more generally its functioning capabilities are provided by the wheel-terrain contacts. Such contacts involve complex phenomena. A common way to represent them is to consider the interaction force system transmitted from the terrain to a wheel resolved about one point of the wheel and represented with a resultant force and a moment. This point will be termed *the contact point* of the wheel. We note that this is generally a point determined by its spatial location, i.e., it is not the same material point of the wheel at all times, but rather the point which is always at the interface between wheel and terrain.

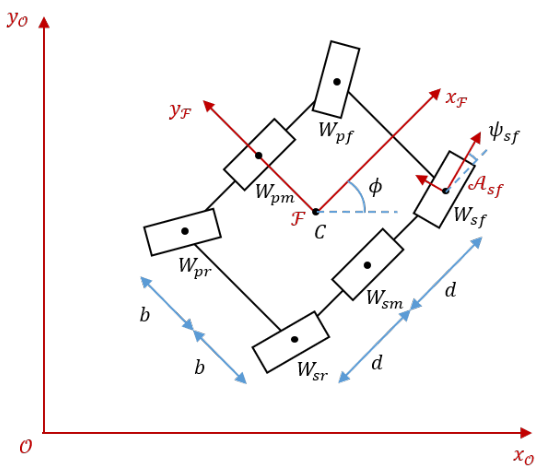

Figure 1: A planar model of a six-wheeled exploration rover.

The most typical operation of a rover is to move on terrain where with a good approximation all wheel contact points are in the same plane, which can be called *the reference plane*. In such a case the motion of the chassis can be considered as planar motion parallel to this reference plane. This is the operation that we address in this paper, focusing particularly on six-wheeled rover configurations that can be modelled with the kinematic diagram in Fig. 1.

In this model we can consider the connection of each wheel to the chassis with a kinematic pair that allows for relative rotation of the wheel with respect to the chassis about two axes: the steering axis, and the wheel rolling axis. Both of these are fixed relative to the chassis. Normally, the connection of a wheel to the chassis is more complex and a suspension mechanism is involved. However, for operation on flat terrain the characteristic modes of interaction between wheel and chassis can be captured by considering such simplified connection.

The motion of the articulated mechanical system of the rover is decomposed to two parts based on the motion of the chassis. The first part includes the model representing the motion of the chassis parallel to the reference plane and the three-dimensional motion of the wheels that comes from their rotation about the rolling and steering axes. The second part of the model includes the motion of the chassis and the wheels perpendicular to the reference plane. This decomposition relates to the representation of the terrain reaction forces developed under the wheels. For that purpose we can use the terramechanics relations [1] to represent the normal, longitudinal, and side forces transmitted from the ground to the wheel.

A key aspect for the modelling of the terrain reaction force system is to know the sinkage of a wheel in the direction normal to the reference plane, which also represents the wheel-terrain contact surface. To determine this sinkage we need to consider the dynamics of the system associated with that direction and also constitutive relations that characterize the relationship between normal forces and sinkage. For this purpose the whole mechanical system of the rover, i.e., chassis, suspension, wheels, can be modelled as one single body along the direction normal to the reference plane. The constitutive relation for the pressure-sinkage or normal force-sinkage pairs comes from basic terramechanics experiments. The main issue is that this constitutive relation does not include time dependence and as such is only applicable for static cases. Using this in a dynamics model leads to artificial oscillations [2], which have to be eliminated.

On the other hand for the case of a rover it can be reasonable to assume that for the normal direction a quasi-static load case will be the most dominant to determine the force distribution and the related sinkage. Therefore, a main element in our approach is to decouple the rover model to static model along the direction normal to the reference plane to determine sinkage first, and then in a second step consider a dynamic model that represents the motion of the chassis parallel to the reference plane and the motion of the wheels together with the traction, resistance, and side forces transmitted from the terrain. These forces are determined using the sinkage calculated in the first step using the static model.

The dynamic model is also constructed in a form that can be easily incorporated in an estimation algorithm and makes it possible to use a regular Kalman filter instead of an extended Kalman filter [3, 4]. This generally makes the algorithm much less complex. This is particularly due to the use of generalized velocities that represent scalar components of the absolute velocity vectors of characteristic points of the chassis and the wheels, and separating the velocity and position estimation steps. We will describe this in detail in the presentation, and will also illustrate the results of the model and algorithm with experiments performed using a rover prototype.

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