Received: 2 May 2017 | Revised: 13 September 2017 | Accepted: 14 September 2017
DOI: 10.1002/rob.21761

SURVEY ARTICLE

WILEY

Slippage estimation and compensation for planetary exploration rovers. State of the art and future challenges

Ramon Gonzalez | Karl Iagnemma

Robotic Mobility Group, Massachusetts Institute of Technology, Cambridge, Massachusetts

Correspondence
Ramon Gonzalez, Robotic Mobility Group, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307.
Email: ramon@robonity.com

Funding information
Field experiments with LATUV rover were framed under the STTR Contract NNX15CA25C funded by NASA.

Abstract
Future lunar/planetary exploration missions will demand mobile robots with the capability of reaching more challenging science targets and driving farther per day than the current Mars rovers. Among other improvements, reliable slippage estimation and compensation strategies will play a key role in enabling a safer and more efficient navigation. This paper reviews and discusses this body of research in the context of planetary exploration rovers. Previously published state-of-the-art methods that have been validated through field testing are included as exemplary results. Limitations of the current techniques and recommendations for future developments and planetary missions close the survey.

KEYWORDS
IMU, LATUV rover, Lunar Roving Vehicle, machine learning, Mars rovers, visual odometry

1 | INTRODUCTION

The future of mankind is to colonize other worlds from the Moon to Mars and other near-Earth objects like asteroids. However, before achieving such a challenging endeavor robots will have to precede human missions to these targets. But even when human beings will be ready for walking on the surface of those bodies, robotic assistance will still play a key role in the scientific exploration and their everyday life. NASA's near-term high-priority plans include robotic missions to the Moon, Mars, and other bodies in the solar system.[1] The success of these missions will be critically dependent on mobile robots that are able to safely traverse a complete set of different environments such as impact craters, channel beds, cliffs, regolith soil, ice, wind-blown dust, and shadowed areas, among others.[2]

Scientific contexts for Martian and Lunar exploration illustrate the need for innovation in terrain mobility. An effective way to leverage NASA's extensive expertise in rover design and mission planning, while avoiding the risk associated with new mobility paradigms (e.g., climbing) is to develop new approaches to optimizing rover control to both maximize traction and minimize risk of entrapment. Such control approaches can potentially operate without the need of any additional sensors (beyond a standard baseline rover sensor suite), thus minimizing additional cost, mass, and volume.

This paper focuses on reviewing the state of the art in one of the key phenomena dealing with terrain mobility: slippage.[3–6] In particular, this survey analyzes the slippage estimation and compensation methods that appeared in the field of planetary exploration robotics. It is important to remark that slippage does not necessarily mean loss of traction. In fact, a certain amount of shear displacement and sinkage (physical phenomena influencing slippage) are required in order to generate traction in wheeled ground vehicles.[7] The problem is that excessive slip does cause a loss of tractive effort and rover speed, and eventually to rover entrapment.

The importance of the topic covered in this survey has been clearly understood from the very beginning of all major lunar/planetary exploration missions. For example, plenty of slip-related experiments were conducted back in the 1960s–70s in the context of the Apollo's Lunar Roving Vehicle (LRV).[8] Those studies showed that for a given slip, the pull increased with increasing soil strength. Likewise, for a given pull or slope, the slip was less in firmer soil (higher soil strength). Those studies also played a significant role in the design of the LRV's wheels.[9] Next, in the 1970s–80s, slip compensation was considered as a critical module of the navigation control architecture in the early design concepts of Mars rover missions.[10]

Slippage is a measure of the lack of progress of a wheeled ground vehicle while driving on certain terrains (e.g., sandy slopes, ripples, and low-cohesion soils). Slippage can lead to significant slowdown of the vehicle, inability to reach its predefined goals, or, in the worst case, getting entrapped without the possibility of recovery.[11] Accordingly, the success of a science mission, in the context of planetary exploration rovers, is critically dependent on the rover's capability to detect and reduce slip.[12] All lunar/planetary exploration missions involving ground vehicles or mobile robots have suffered slippage-related hazards during their lifespan. Table 1 summarizes some of the most significant lunar/planetary exploration missions involving ground manned vehicles and mobile robots. The worst situation dealt with the MER Spirit rover trapped in a sand dune in 2009. After numerous attempts to free the rover, the mission was declared concluded on May 24, 2011.

© 2017 Wiley Periodicals, Inc.

TABLE 1 Historical review of the most significant slip-related hazards faced by lunar and planetary exploration vehicles

Mission/Vehicle	Date of Event	Terrain, Place	Hazard	Action	Ref.
MSL, Curiosity	May, 2015	Deformable terrain (Mars, Gale Crater, near Mount Sharp)	High-slip events	Turn back the rover before she could become entrapped	106
MSL, Curiosity	February, 2014	Deformable terrain (Mars, Gale Crater, Dingo Gap)	High-slip events (sinkage up to 0.15 [m] and slippage up to 77 %)	The route was manually biased to avoid soft sands	3
MER, Opportunity	April 6, 2010	High windblown ripple dominated by loose, poorly sorted basaltic sands (Mars, Meridiani Planum)	Opportunity experienced significant slippage (up to 40%)	More power to the wheels and extra slip checks	22
MER, Spirit	May 1, 2009	Soft soil (Mars, Gusev Crater, Home Plate)	Spirit got entrapped with no possibility of recovery	Several recovery techniques (mission concluded on May 24, 2011)	100
MER, Opportunity	April 26, 2005	Sand dune (Mars, Purgatory Ripple, Meridiani Planum)	Opportunity got entrapped	Recovery actions (for 5 weeks)	101
Pathfinder, Sojourner	August 21, 1997	Deformable terrain (Mars, Ares Vallis)	The right front wheel was parked on a small rock, perching the left front wheel above the surface	Engineers teleoperated the rover to a safer place	102
Apollo, Lunar Roving Vehicle (LRV)	April 1971 (Apollo 15)	Deformable terrain (Moon, Hadley-Apennine)	LRV got entrapped in soft soil (sinkage around 0.13 [m])	Astronauts pushed the vehicle (due to the low lunar gravity (LRV = 38 [N]))	17
Luna 21, Lunokhod 2	January, 1973	Soft soils on the inside walls of craters; the soil was particularly soft at the base of slopes (Moon, Mare Serenitatis)	Normal wheel sinkage was 0.02 [m]. Wheel sinkage was > 0.2 [m] near impact craters	Engineers teleoperated the rover to a safer place	103

The slippage phenomenon is due to numerous and complex processes (e.g., inflation of the wheel, load on the vehicle, velocity).[7] In the context of planetary exploration rovers, the dominant factor is related to the wheel–soil interaction. That is, the properties of the soil under the wheel (e.g., bulk density, cohesion, angle of internal friction) and the wheel's own parameters (e.g., design, weight).[4,13] Other key issues directly influencing slippage are the vertical stress and sinkage. These increase the rolling resistance, and hence, reduce the net traction.[14,15]

It can be thought that limiting slippage could just be a matter of commanding the planetary exploration rovers over well-cemented terrains. However, this decision may mean new hazards. In fact, since late 2015, JPL's MSL mission planners have been dealing with punctures and tears in Curiosity's aluminum-alloy wheels, which might eventually fracture the wheel, and halt the progress of the Mars rover. This damage occurred when the rover drove over angular, embedded rocks.[3,16] This led to directing the rover to traverse in valleys where sands cushioned wheel loads.

This paper is organized as follows. Section 2 provides a descriptive characterization of the terrains found in lunar/planetary missions. Section 3 reviews state-of-the-art methods of both slippage estimation and compensation. It also includes field tests validating some of those methods. Section 4 summarizes and discusses the implications of the survey addressed in the previous section. Section 5 concludes the paper and highlights recommendations and future directions.

1.1 | Definitions

Slippage: metrics measuring the lack of progress experienced by a wheel (or driving implement) due to its interaction with the terrain (soil displacement and sinkage). Excessive slippage does cause a loss of tractive effort and rover speed and, in extreme cases, embedding and entrapment.

Embedding: anomalous situation experienced by a rover after near 100%-wheel slip and high sinkage, the rover is still able to make progress in at least one direction by using various maneuvers of the free wheels.

Entrapment: critical situation experienced by a rover after 100%-wheel slip, there is no possibility to make progress in any direction and the mobility capability of the mission ends.

Slippage estimation: set of actions and sensors devoted to measuring/estimating those variables concerning wheel slip (e.g., angular wheel velocity and rover velocity).

Slippage compensation: set of control actions devoted to reducing wheel slip, and thus, limiting the rover experiences embedding and entrapment.

Proprioceptive sensor: sensor that only requires input(s) from the rover (e.g., IMU).

Exteroceptive sensor: sensor that requires input(s) from the environment and the rover's surroundings (e.g., visual camera).

2 | CHARACTERIZING THE PLANETARY EXPLORATION ENVIRONMENT

What makes Mars or the Moon interesting to scientists also makes them challenging to a ground vehicle or autonomous mobile robot: its unique and challenging terrain. Numerous missions to those two bodies demonstrated that the terrain to be traversed is not limited only to hard surfaces, but also to loose materials and steep slopes (e.g., sand dunes). Furthermore, primitive bodies such as asteroids and comets

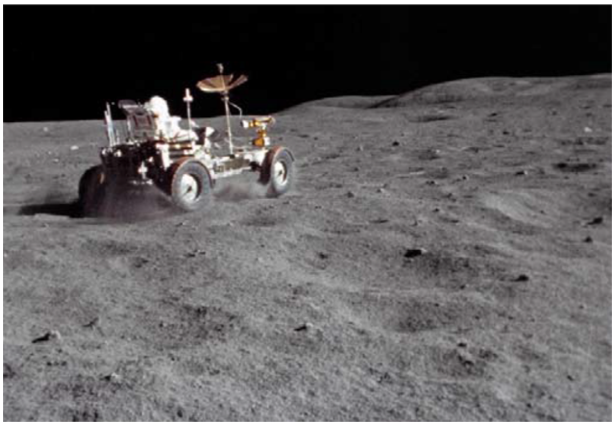


FIGURE 1 The Apollo Lunar Roving Vehicle driven by astronaut John W. Young during the mission Apollo 16 at the Descartes landing site on April 21, 1972. Note the sinkage of the rear wheels due to the soft soil conditions (Image credit: NASA)

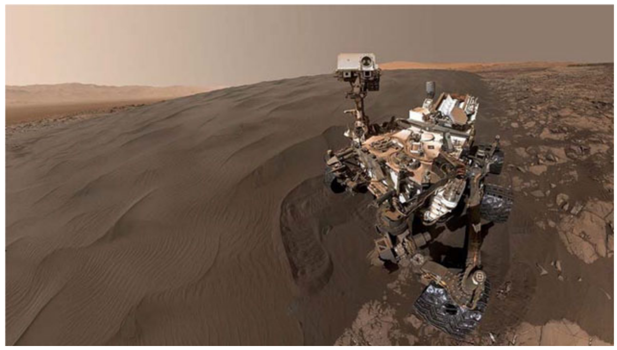


FIGURE 2 MSL Curiosity rover on both a field of sand ripples and a bedrock (Image credit: NASA)

often consist entirely of fine grained particles or soft materials. This section reviews the main challenges experienced in those bodies from a mobility standpoint. The study focuses on the local regions traversed by the Apollo's LRV and the Mars rovers. It is neither adequate nor possible to generalize the physical properties of these regions to the entire celestial body.

The Apollo's astronauts described the lunar terrain as very uneven, having a smooth texture and only small areas of fragmental debris. A wide variety of craters were encountered. Approximately 90% had smooth, subdued rims, which were, in general, level with the surrounding surface. Slopes of up to approximately 15% were encountered. The surface material varied from a thin powdered dust (where the boots penetrated to a depth of 5–8 cm) to a very firm rille soil (a fissure or narrow channel on the surface), which was penetrated only to a depth of 0.6–1.25 cm by the boot. The tracks of the LRV were prominent on the surface and very little variation of depth occurred when the load on all four wheels were equal. On steep slopes, where increased loads were carried by the downhill wheels, deeper tracks were encountered (2.5–5 cm in depth),[17] see Figure 1. This description clearly demonstrates the challenging conditions of the lunar terrain where significant sinkage may appear, and eventually lead to vehicle entrapment. These conditions were experienced by the Apollo's 15 and Apollo's 16 astronauts (Lunar Grand Prix).[17,18]

Future robotic missions to the Moon may include the Aitken basin at the lunar South Pole, where the Committee on the Scientific Context for Exploration of the Moon states that: "Within it lie samples of the lower crust and possibly the lunar mantle, along with answers to questions on crater and basin formation, lateral and vertical compositional diversity, lunar chronology, and the timing of major impacts in the early solar system."[19] Polar basins also are likely to contain volatiles like water that are crucial to the establishment of permanent habitation on the Moon.[20] However, lunar polar regions remain in shadow. This represents a challenge to the traditional vision-based navigation systems and makes thermal design exceedingly difficult.

The Spirit rover moved across the Gusev plains from 2004 to 2009 reaching a remarkable distance of 7.73 km. The landing region involved a generally flat plain with about 5% of the area covered by relatively small (tens of cm size or smaller) rocks. Most of the rocks were angular to subangular, and a small number were rounded.[21] After the first months, Spirit was commanded towards the top of a hill called Husband hill in the complex Columbia Hills. Opportunity rover has been roving Mars from January 2004. She has accomplished an astonishing distance of almost 45 km (August, 2017).[22] Opportunity has been working in one location: Meridiani Planum, where various craters have been explored (e.g., Victoria and Endeavour craters).

Spirit and Opportunity experienced several mobility hazards dealing mainly with sandy dunes of very low cohesion (around 10 kPa or less).[23] Those conditions frequently led to slippage.[5,24] The formation of these areas is partially due to giant dust storms that appear one to three times yearly, near the time of Mars perihelion, and which have blanketed much of the planet with an extremely fine-grained material, and some rocks are frosted on top with eolian-transported material.[3]

Regarding the mobility of MSL Curiosity rover, which landed on Gale Crater on August 2012,[104] a new hazard was soon encountered. The origin of this hazard is related to the wind effect. On Earth, wind produces small ripples or large dunes. On Mars, however, wind produces a much more challenging phenomenon: megaripples,[3] see Figure 2. As shown in Ref. 3, traversing extensive megaripple fields, with ripple crests separated by wavelengths comparable to the front-to-back MSL wheel distances, produces complex slip as a function of rover tilt, with extreme slip values up to 77%, and trailing wheel sinkages up to 0.15–0.17 [m]. In addition to the high risk of rover entrapment, megaripples lead to increased wheel actuator currents, and in cases where one or more of the wheels carried more load, increased wheel sinkage and associated compaction resistance.

3 | LITERATURE REVIEW

Slippage or slip, s, is in general defined as the difference between the velocity measured by the wheel, ωr, and the linear velocity of the wheel's center, v, that is,

$$s = 100 * \begin{cases} \dfrac{\omega r - v}{\omega r}, \text{(driving)} \\ \dfrac{\omega r - v}{v}, \text{(braking)} \end{cases} \tag{1}$$

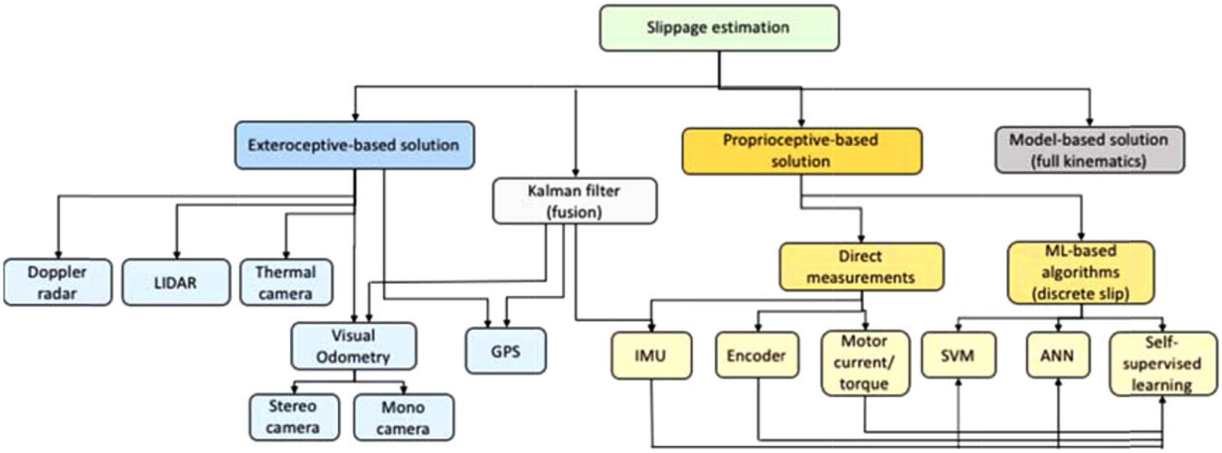


FIGURE 3 Most common slippage estimation approaches in the context of planetary exploration rovers

where ω is the angular wheel velocity and r is the effective wheel radius.[7] It is worth to remark that slippage can also be defined as

$$s = 100 * \left(1 - \frac{d_A}{d_C}\right), \quad (2)$$

where d_A is the actual distance traveled by the robot and d_C is the commanded distance.[3]

According to the previous definition, slip estimation techniques can be classified depending on the methods/sensors used for estimating/measuring the angular wheel velocity and the linear body velocity.

3.1 | Slippage estimation

As Figure 3 shows, slippage estimation methods can be classified according to two categories in a broad sense. On the one hand, proprioceptive-sensor-based solutions estimate slippage only once the robot actually traverses a given terrain, this approach may mean a high risk of vehicle entrapment. However, they represent the most accurate way to estimate slip. On the other hand, exteroceptive-sensor-based solutions predict slippage of the terrain ahead of the robot from a certain distance. However, because many of these approaches deal with cameras, their estimations are solely based on the topmost terrain surface (texture). This fact may lead to wrong conclusions since terrain trafficability is mainly dictated by the particles below the topmost layer.[11,25,26] A third category—composed of the other two—fuses data from proprioceptive and exteroceptive sources through mathematical tools like the Extended Kalman Filter (EKF). Finally, model-based solutions employ the full kinematic model in order to estimate the actual rover motion.

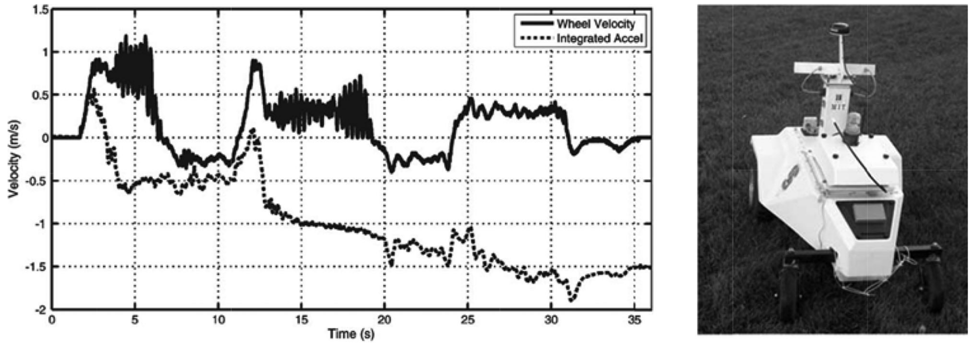
3.1.1 | Proprioceptive-based slippage estimation

One of the first methods found in the literature for estimating slip was proposed by Prof. Wong in the 1960s–70s. Slip was directly measured by comparing signals from a wheel placed in front of the robot/vehicle.[7] This method has also been applied in more recent publications.[27,28] This approach had many problems: the system had to be modified, and the uneven surface increased the error in the wheel encoder reading, which led to inaccurate slip measurement. These limitations motivated the development of indirect methods based on other sensors onboard the robot.

A simple approach relies on comparison of wheel velocities to a robot body velocity estimate derived from integration of a linear acceleration measurement in the direction of travel (e.g., using accelerometers).[29–32] Nevertheless, even with high-quality inertial sensing, accurate estimation of body velocity is subject to error and drift,[33,34] see Figure 4.[35] proposed a method of aiding the inertial estimate using vehicle constraints (constant acceleration); however, the method is not appropriate on uneven, low-traction terrain. An accurate method solving these issues was described in Ref. 36. This method, called 3D-Odometry, fused different types of sensory inputs: inertial measurement unit (accelerometers, gyros) and visual odometry (VO). However, this method only worked for mobile robots moving on flat and even terrain.

A more robust approach was depicted in Ref. 37. Here, an EKF fusing information from wheel encoder, IMU, and GPS measurements creates an estimate of the robot's longitudinal velocity. The drawback of this strategy is that GPS measurements are not available in planetary missions. A Kalman filter was also employed in Ref. 38 for combining inertial measurements with motion estimates from a VO module. The main weakness of this method is that it mostly relies on visual information, making it difficult to apply to heterogeneous lighting conditions (e.g., shadowed regions in the lunar poles).

A simple algorithm for detecting embedding in soft soil running on the MSL rover (and co-developed by Dr. Iagnemma, coauthor of this paper) is based on an algorithm that averages wheel current over a 20-s window. Such average motor current is then compared with a pre-determined safe threshold. Despite the relatively simple nature of this implementation, it is currently in continuous use on Mars, and has already demonstrated its effectiveness by halting the progress of Curiosity on sol 672 (June 27, 2014), when a high slip was experienced while crossing sandy ripples.[105] The most notable limitation of this approach is that it does not work when climbing slopes since wheel currents are naturally higher for climbing. Neither does it work on uneven soil surfaces, where varying wheel loads give rise to varying



(a) Performance of the IMU vs the wheel encoder *(b) LAGR robot*

FIGURE 4 Performance of estimating robot body velocity by integrating measured acceleration on a wheeled mobile robot traveling on a grassy, rolling outdoor terrain. It can be observed that at low speeds accelerometer errors dominate, causing the velocity estimate to quickly diverge[33]

current thresholds. Another solution based on motor current (motor torque) is to estimate the wheel's linear velocity by means of an empirical function table where velocity is obtained in terms of the motor torque.[39] Motor current is also related to wheel slippage in Ref. 40. However, this technique required terrain-specific parameters and solving in real-time the complex Bekker–Wong model. For that reason, this solution can be considered as undesirable in the context of planetary exploration rovers where low-performance computers are often employed.

A new field of study deals with the estimation of slippage in terms of discrete classes. More specifically, machine learning algorithms identify various degrees of slippage by using a set of features (i.e., proprioceptive sensor signals). In this way, the problem of slip detection reduces to a classification problem (discrete slip classes). One of the first papers belonging to this new field is Ref. 41. Here, the authors propose a methodology where machine learning algorithms are used for detecting three levels of slip or discrete slip classes (i.e., low slip, moderate slip, and high slip). Proprioceptive sensing (i.e., IMU, motor current, and encoders) is employed. Figure 5 shows the performance of various learning algorithms while considering the data set collected by a planetary exploration rover, LATUV rover developed by ProtoInnovations LLC, in real conditions. The best result is obtained by the Support Vector Machine (SVM) algorithm. The semantic Self-Organizing Map (SOM) and Artificial Neural Networks (ANN) algorithms exhibit similar performance. The distance-based SOM and K-means perform poorly especially in the three-class case.

The possible argument with the definition of slippage as a discrete variable is the selection of the number of discrete classes and the boundaries between classes. Note that machine learning has also demonstrated its suitability in the context of terrain classification. For example, a SVM algorithm is trained by using IMU measurements.[33,42,43] ANN have also been used for terrain classification using proprioceptive sensors.[44,45] The work performed in Ref. 46 shows a vibration-based terrain classifier that takes the role of a “supervisory” classifier and the “supervised” classifier is a vision-based terrain classifier. Training data for the vision-based classifier are extracted from forward-looking stereo images stored in memory and recalled when the rover classifies a previously observed terrain patch using proprioceptive sensors.

3.1.2 | Model-based slippage estimation

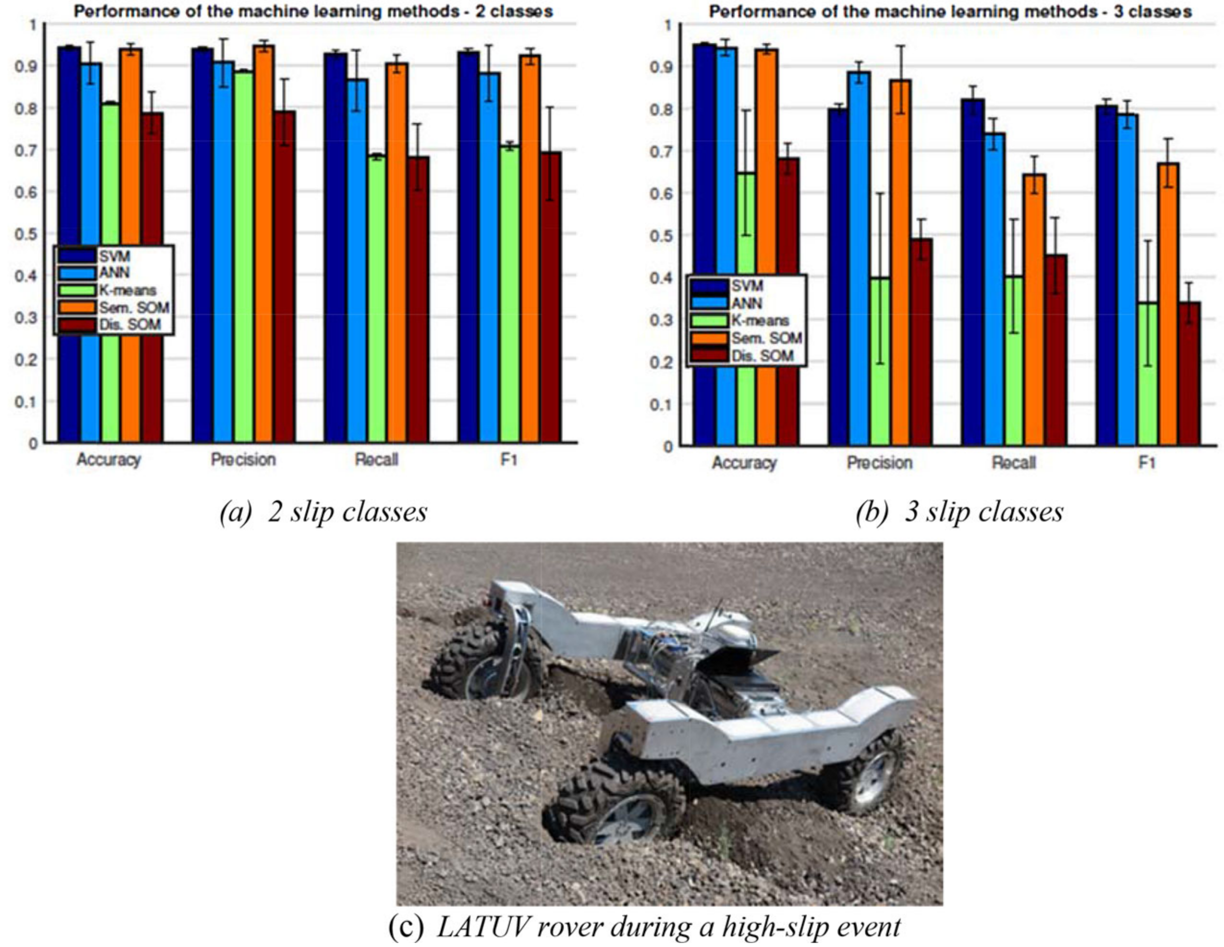
Model-based slippage estimation can be also considered in this section. The idea is to obtain the velocity of the robot in terms of its full kinematics. For example, Ref. 47 proposed a method that estimated the motion of MER rovers using the full kinematics state of the rovers, encoder data, and a digital elevation map obtained from stereo images. A similar solution is adopted in Ref. 38. Here, the forward kinematics of a Mars rover research platform is used for estimating rover motion given the wheel rates, and the rocker, bogie and steering angles. Slippage is obtained after comparing that previous estimation to the velocity estimated by a Kalman filter fusing IMU and Visual-Odometry data. The motion profile of the entire rover is numerically evaluated by using a wheel-and-vehicle model in Ref. 48. This model comprises the wheel–soil interaction and the articulated multibody dynamics of the robot's body and chassis.

The major disadvantage of these strategies is that the models are simplified representations of the real world; therefore, slippage estimations can be quite inaccurate. Furthermore, solving mathematical models may lead to demanding computation in the low-performance computers onboard planetary exploration rovers.

3.1.3 | Exteroceptive-based slippage estimation

One successful and accurate method for measuring the actual velocity of a robot, and hence slip, is to use active or passive beacons. In this category, the use of RTK-GPS accounts by many publications.[49,50] Alternative methods to RTK-GPS include the use of ground-based beacons. For example, ground magnet markers were used in Ref. 51 to infer the position of a robot and the side-slip. In the work presented in Ref. 26, the velocity of a robot was measured by using a set of visual targets (AprilTags).[52] The drawback of these solutions is that no beacons (satellites or ground-based markers) are available in the lunar/planetary environment. This motivates why alternative methods are proposed in this body of research.

One of the most extended techniques for estimating rover slip is based on VO.[11,53–55] For example, Ref. 11 proposed an approach to predict slip from a distance using stereo imagery. To address this issue, terrain appearance and geometry information are correlated with the measured slip. This relationship is learned using a receptive



(a) 2 slip classes

(b) 3 slip classes

(c) LATUV rover during a high-slip event

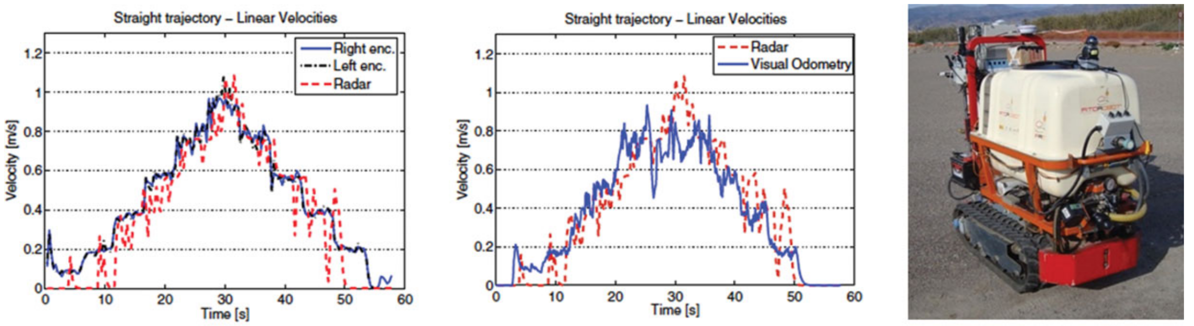
FIGURE 5 Performance of the compared machine learning algorithms using the data collected by the LATUV rover. Notice that these plots show the mean and standard deviation of ten experiments where hold-out cross-validation was used[41]

field regression approach. In the end, slip is predicted online remotely from visual information only (terrain slopes). A similar idea appeared in Ref. 56. The robot learns and adapts its control with respect to the geometry of the terrain (vegetation condition). Although VO can be an accurate method for slip estimation, it is computationally expensive, which can negatively impact the mean rover drive speed (the rover may move slower to process the terrain information). Field-Programmable Gate Arrays (FPGAs) have resulted in an efficient platform to run VO algorithms on planetary exploration rovers.[57] A second limitation of VO is that on featureless scenarios (e.g., sand dunes) or on shadowed areas (e.g., lunar poles), the number of detected and tracked features is low, and can lead to poor accuracy of motion estimate[58,59] proposed an algorithm that dynamically switches between several detectors increasing the performance of VO in an untextured natural terrain. However, this strategy was validated over a small dataset and only for terrain classification purposes.

Another way to estimate slip by means of visual cameras appeared in Ref. 60. Here, slip is estimated by visually observing the traces produced by the wheels of a robot on a soft, deformable terrain. The primary sensing device comprised a rearward-facing camera. A downward-looking camera was employed in Refs. 61 and 62 for measuring the actual forward velocity of a tracked mobile robot. This strategy implemented a particular VO-based algorithm (i.e., template matching). In the work presented in Ref. 63, telecentric lens inserted in front of a downward-looking camera provided a constant image scale factor regardless of the distance between the lens and the ground. A comprehensive comparison among VO systems using lenses with three different focal length lenses was addressed in Ref. 64.

An interesting alternative to visual cameras comprises sensors that make use of other frequencies in the electromagnetic spectrum. For example, thermal cameras have demonstrated promising abilities in discriminating various terrain types.[26,65,66] LIDARs have been successfully applied to terrain mapping and path planning in the context of planetary exploration rovers.[67] Camera-LIDAR fusion was introduced in Ref. 68 as a feasible technique to overcome the limitations of either of these individual sensors for planetary exploration. Unfortunately, these technologies have yet to be employed to the particular problem of estimating slippage.

Doppler radars have shown their suitability in measuring the actual velocity of a robot or vehicle, and hence, in slippage estimation.[27,53] However, as those papers show the use of this sensing technology is only valid for velocities higher than 1 [m/s] due to the low acquisition limit of the radars. Figure 6 shows the result of an experiment moving the tracked robot detailed in Ref. 53 at velocities in the



(a) Doppler radar vs wheel encoders

(b) Doppler radar vs visual odometry

(c) Fitorobot during field tests

FIGURE 6 Performance of two different approaches for measuring the linear velocity of a robot: Doppler radar and VO[53]

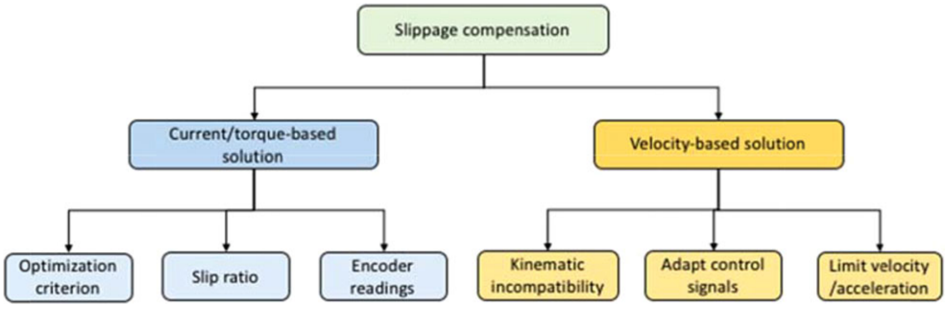


FIGURE 7 Most common slippage compensation approaches in the context of planetary exploration rovers

range {0, 1} [m/s]. In this case, the theoretical velocities obtained from encoders are also plotted (labeled as "Right enc." and "Left enc."). As observed, the Doppler radar does not work properly at velocities lower than 0.4 [m/s]. This erroneous behavior is due to the resolution of the sensor. The VO-based approach works properly for low velocities. However, it produces an unsatisfactory result for velocities close to 1 [m/s]. It is worth noting that when the robot moved at these velocities, a blur effect occurred in the images.[61] This issue explained the poor performance of the VO-based algorithm at high velocities (>0.8 [m/s]).

3.2 | Slippage compensation

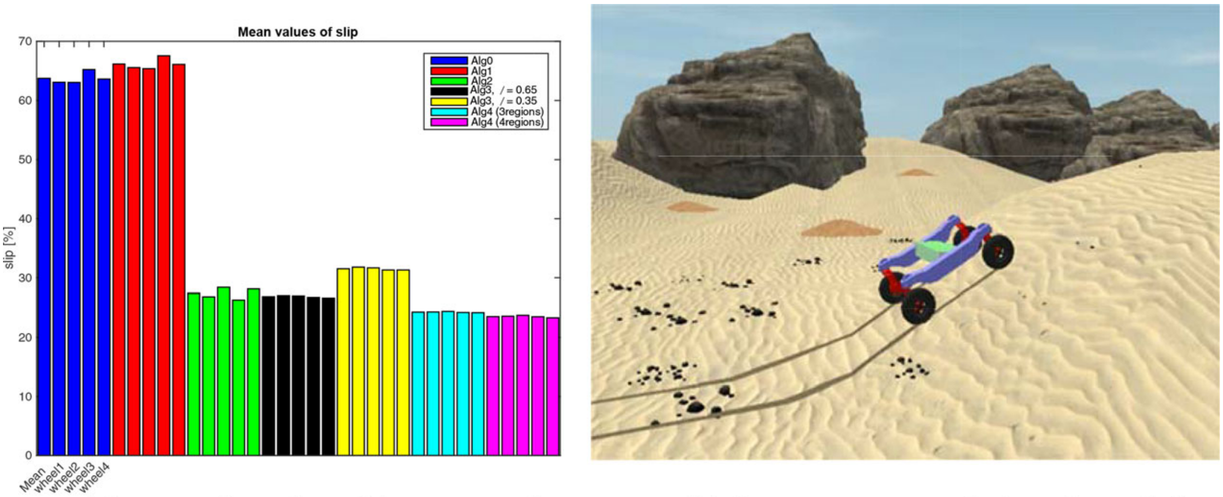
High levels of slippage can prevent the robot from maintaining adequate wheel traction. Furthermore, if excessive force is applied to a terrain region, the soil may fail and induce excessive wheel sinkage, which may lead to entrapment. Here, the two paradigms dealing with slippage compensation are reviewed (Figure 7): torque-based traction control and velocity-based traction control.

Substantial work has been performed on traction control of passenger vehicles operating on flat roads.[69] However, these approaches rely on mechanical torque distribution systems, such as differential, which mobile robots are not usually equipped with. For that reason, researchers involved in planetary exploration missions have had to propose alternative strategies. Furthermore, in the case of planetary exploration rovers, slippage is produced by the nature of the terrain (soil failure), hence, this scenario and its associated wheel–soil interaction is fairly different from the paved roads involving passenger vehicles.

3.2.1. | Motor-current/torque-based slippage compensation

Some approaches try to avoid slip generating control signals such that the soil never fails. Those strategies rely on some kind of optimization criterion where control actions depend on parameters dealing with the strength of the terrain. The pioneering work[70] presents an optimization criterion involving the estimates of wheel–terrain contact angle and soil characteristics that ensure no soil failure and maximizes traction over rough terrain (or minimizes power consumption over benign terrain). The strategy was run in real-time resulting in a set of torques. An optimization criterion based on the friction coefficient of a given soil was described in Ref. 71, this strategy was inspired by Ref. 72. The basic idea of the optimal torque control algorithm is to set torques according to the load distribution on the wheels in order to maximize traction. A similar approach was detailed in Ref. 39. However, instead of solving an optimization problem; here, the slip ratio is kept small by limiting the driving torque in such a way that the estimated slip and the desired slip match. This eventually means that the commanded torque does not yield soil failure. Ref. 73 used motor current measurements for adjusting the wheel angular velocities, coming from encoder readings, and affected by wheel slippage. This control algorithm requires some knowledge of the terrain, which is estimated in real-time through a GPS-based method.

Notice that previous approaches are mainly based on the Bekker-Wong terramechanics model.[7] This model is empirically valid in large agricultural or military vehicles. Recent research proposes a new pressure-sinkage model applicable to small, light-weight vehicles such as planetary exploration rovers.[74–76]



(a) *Mean slip value of the compared traction controllers*

(b) *Scenario composed of sandy rippled terrain with significant slope*

FIGURE 8 LATUV rover operating over Mars-analog simulated terrain under various slip-compensation traction controllers. Experiments were run in ANVEL developed by Quantum Signal[79]

The main drawback of the motor-current/torque-based slippage compensation methods is that they rely on complex terramechanics models. Those models usually require numerous parameters that are difficult to measure in real-time. Furthermore, the control actions can become too conservative, thus, limiting the routes or velocities that the robot can actually achieve.

3.2.2 | Velocity-based slippage compensation

Due to the uneven nature of natural terrains, wheel slip is also a result of wheel "fighting." This is called the kinematic incompatibility problem.[77] Unevenness leads to a mismatch between wheel velocities as each wheel experiences different loading/torque profile. This ultimately means a lack of coordination among the wheels. One of the first solutions to this problem, in the context of planetary exploration rovers, appeared in Ref. 77. Here, a voting scheme determined which wheels were deviating from the nominal rover traverse velocity. Next, Ref. 78 proposed an algorithm where rover wheel velocities adapted according to the shape of the terrain considering kinematics relations between them. This strategy inspired the work in Ref. 79 where the contact angle between the wheel and the terrain was used to adjust the commanded velocity of each wheel, see Figure 8. A set of proprioceptive sensors and a kinematic model was employed in Ref. 80 for adjusting individual wheel velocities based on estimates of the terrain slope. Ref. 81 introduced a cross-coupled controller for an all-terrain rover. This strategy compares the wheel encoder pulses to slow down the wheels that are faster and speed up those wheels that are slower than the others. The principal limitation of these solutions is that solving the kinematic incompatibility phenomenon does not completely guarantee slip-free traverses because individual wheels may suffer slip due to the soft nature of the soil.

Other approaches intend to adapt the control signals coming from the motion controller depending on the estimated slip, and, hence, compensate its effect. The pioneering work presented in Ref. 31 proposed the "Fuzzy Logic Encoder Compensation," which compensates wheel slip by adjusting wheel velocity in proportion to a quantified indicator. This indicator comprises readings from different sensors (i.e., motor currents, gyros, tilt sensors). The work in Ref. 38 showed a path following controller that compensates for slip by appropriately modifying the velocities sent to the wheels by means of a slip-augmented inverse kinematic model. In this case, slip is calculated as the difference between the Kalman filter position estimate and the kinematic estimate.[82] presented two different control approaches to compensate for three types of slip, namely, the vehicle longitudinal and lateral slips. One is a model-based feedforward control and the second one is a sensor-based feedback control. A robust predictive controller was introduced in Ref. 53 where the velocity of the wheels is adjusted depending on the estimated slip and on the uncertainty of such estimation (additive uncertainty). That reference also contributed a linear feedback controller and an adaptive controller minimizing the effect of slippage.

There are other control strategies that try to reduce slip by limiting the velocity/acceleration of wheels.[83] This strategy may become unsuitable in practice because, as addressed in Section 2, planetary terrains are intrinsically loose producing a non-controllable slip. That is, the robot will slip although velocity and acceleration are limited.

The main advantage of the velocity-based slippage compensation approaches is that they do not require the knowledge or estimation of complicated parameters dealing with terramechanics models. However, as explained in Ref. 71, their results are expected to be limited in very challenging terrain (e.g., slopes).

4 | DISCUSSION

In order to give a deeper view of the relevance of the topic addressed in this survey, a comprehensive search of the term "slippage" was done

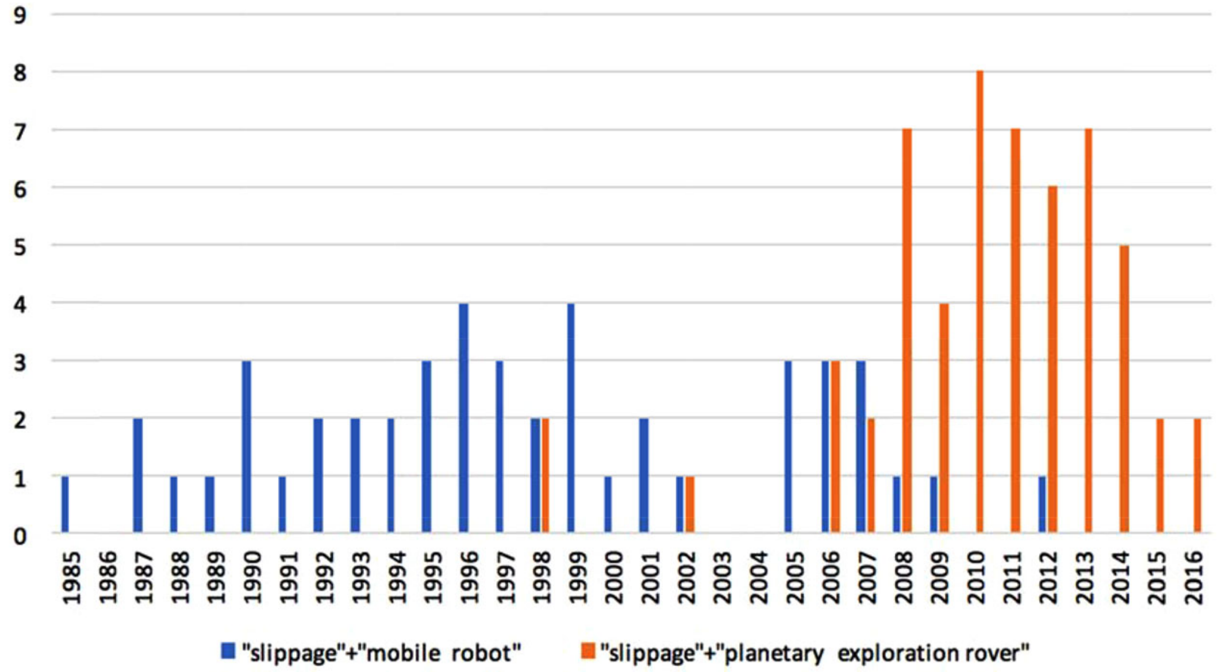


FIGURE 9 State of the art: slippage in mobile robots (on Earth) and planetary exploration rovers

on Google Scholar (104 publications sorted by relevance). In particular, two sets of keywords have been used. The first search deals with the keywords: “slippage” and “mobile robot” (47 publications). The second search is related to the keywords: “slippage” and “planetary exploration rover” (57 publications).

It is worth to note that even though several terrain parameters can be roughly known *a priori* for a specific soil, in practice, the deformation of the soil depends not only on the properties of the soil itself, but also on the vehicle mechanics and the wheel–terrain interaction.[7] For that reason, in this comparison, this broad body of research focused on estimating mechanical and physical properties of a terrain during the vehicle's motion has also been included in the analysis.

4.1 | Slippage in the context of ground mobile robots

The first conclusion after this comprehensive search is that it returns older publications than those obtained with the second search, see Figure 9. Notice that the publications dealing with the terms “slippage” and “planetary exploration rover” significantly increased after the MER rovers arrived in Mars, year 2004. In contrast, the number of publications related to the keywords “slippage” and “mobile robot” decreases after that achievement.

It is important to remark that though both searches returned a similar number of publications, the citations dealing with the first search are more broadly spread than those dealing with the second (20 years vs. 10 years, respectively). Another interesting conclusion is that there is a wide field of research comprising perception/localization methods preventing wheel-based odometry from systematic and non-systematic errors. Notice that these publications do not specifically focus on the lack of traction due to the wheel–terrain interaction, but on features dealing with the inflation pressure, the wheel radius, and similar elements deforming the wheel shape.

Other publications are related to motion control considering slippage as an unknown disturbance that affects the performance of the mobile robot. Some of these control strategies cope with moving the robot at a slow speed to reduce slippage. In general, numerous publications describe slippage as a variable that affects the estimation of the position of the robot and the model of the robot. Slippage is understood as a disturbance that affects motion of the robot.

Regarding the first search, it is important to emphasize that many publications assume pure wheel motion with non-slip conditions. This assumption limits the applicability of the proposed approaches to non-deformable surfaces (e.g., indoor paved scenarios).

4.2 | Slippage in the context of planetary exploration rovers

In contrast to the previous search, here, slippage is understood as a critical variable (major disturbance) that affects the motion of the robot and must be estimated properly and compensated.

Figure 10 shows the result of our comprehensive study in terms of 12 keywords: mechanics, modeling/parameter estimation, slip detection/estimation, simulation/simulation tools, localization, path planning, terrain classification, control/slip compensation, proprioceptive sensors, exteroceptive sensors/VO, Moon, and Mars. This set of keywords have been chosen according to our experience and to the most popular keywords included in the publications under study.

A significant body of research deals with modeling the wheel–terrain interaction. The main conclusion drawn from this topic is that these models usually require numerous and complicated parameters to

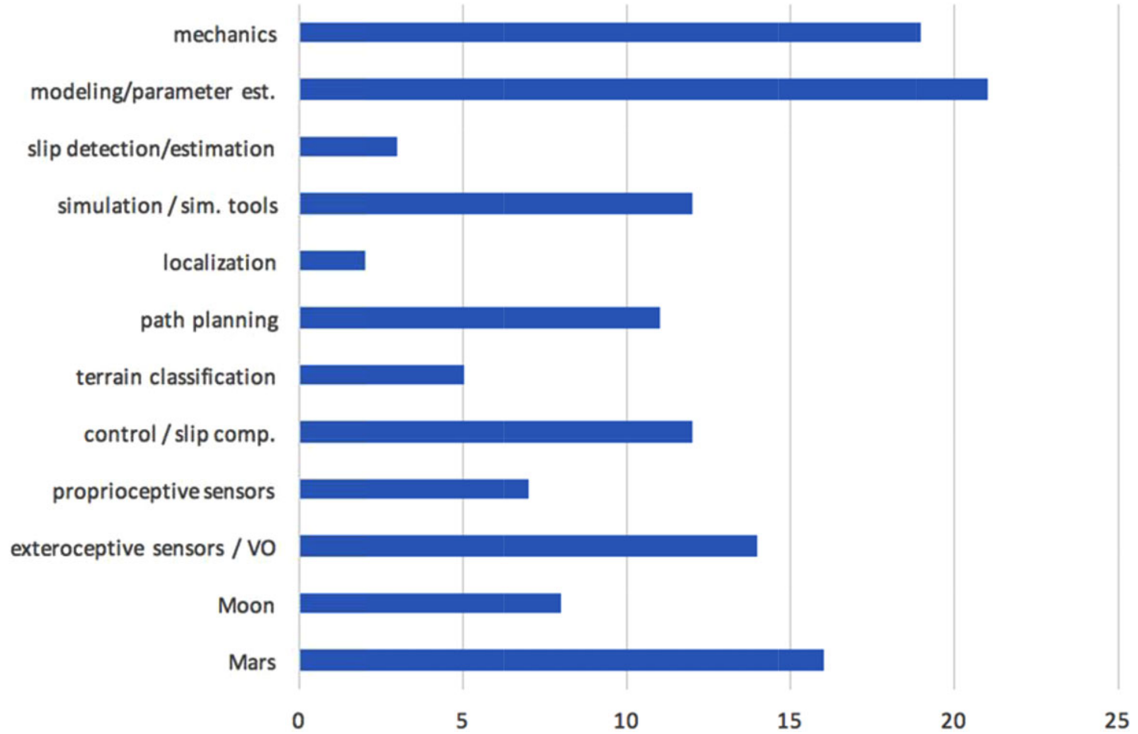


FIGURE 10 Main topics/keyword of the surveyed papers

be estimated in real-time, so numerous publications rely on simplified forms of classical terramechanical equations. These new equations try to be computationally efficient and dependent on measurements provided by the sensor suite available onboard the rover.

The second trending concern copes with analyzing the performance of various mechanical aspects of the rover such as: wheels design, lightweight chassis, and design of the locomotion system, among others. This category also involves numerous publications where single-wheel testbeds and rover testbeds are built for verifying the mobility of wheels and rovers over a variety of Mars- and Lunar-analog terrains. These testbeds offer the possibility of changing the slip ratio as well as accurate measurements of the forces and moments acting on the wheel and the wheel's velocity. For that reason, they are often used for validating and tuning wheel–terrain interaction models.

The application of exteroceptive sensors constitutes the third major topic. Various publications take advantage of the predicting capabilities of visual cameras for planning the next waypoint to be reached by the planetary exploration rover. While these algorithms are significant accomplishments and increased level of maturity since MER rovers arrived in Mars, they may lead to significant drawbacks. For that reason, various publications focus on investigating new descriptors and features to be tracked between consecutive images. Another key area uses the information coming from the cameras to estimate the motion of the rover, this includes the well-known approach, VO. VO is also used for slip prediction from a distance. Other publications study new cameras like telecentric cameras, which maintain the same field of view regardless of the distance between the camera and the ground. The advantage of LIDARs was also exploited by some authors.

Simulation tools comprise another important research area. A specific software was implemented facing the deployment of planetary exploration rovers on Mars- or Lunar-analog scenarios. These simulations may lead to new rover designs and controls. However, due to the vast variety of terrain components and terrain types on Mars or the Moon, those computer simulations may lead to unrealistic and inaccurate results, especially, in those simulations focused on analyzing the performance of the mobility of the rovers.

The result obtained for the concepts: “traction control” and “slippage compensation” demonstrates the importance of these topics. Many of those studies present a complete navigation architecture: path planning and VO for generating the next waypoint to be reached and path following algorithms for controlling the position of the robot. Finally, slippage compensation algorithms ensure an efficient and reliable navigation.

Another interesting conclusion from this survey is that the number of publications referring to Mars or Mars-analog sites is double the number of publications citing the Moon. This result is not altogether unexpected as there are mobile robots operating on Mars right now. However, it also demonstrates a lack of experience with regard to the particular features of the lunar environment.

5 | CONCLUSION AND FUTURE CHALLENGES

The number one requirement of any robotic planetary exploration mission is how to get the maximum scientific value during the rover's working hours. To successfully achieve that goal, two key design issues must be addressed: (1) how to keep the rover moving at maximum safe speed, and (2) how to make sure the rover is physically able to traverse the terrain needed to reach the desired scientific target. These two issues are especially challenging when the planetary exploration rover must traverse soft soils and/or ascend/descend slopes.

The first challenge requires the implementation of a safety layer in the navigation control architecture that detects and predicts hazards in the environment. This safety layer must combine the accurate properties of proprioceptive sensing and the prediction abilities of exteroceptive sensors. Although, visual cameras have been vastly used in previous planetary exploration missions, they present a significant limitation in that they are only valid for "visual" features of the terrain. However, it is well-known that the wheel–terrain interaction is mainly dictated by the layers below the topmost layer of the soil.[4] This reasoning motivates the use of other technologies such as thermal cameras[66,84] and ground penetrating radars,[85–87] among others.

It is true that carrying out an investigation on the mechanical and locomotion aspects of planetary exploration rovers constitutes an inevitable technological trend. However, there are not many papers dealing with active or hybrid wheeled locomotion concepts which may improve traction under high-slip events.[88–90] Additionally, new wheel designs and patters in the wheel structure (e.g., grousers) and elastic-deformable wheels should be further investigated for the specific purpose of minimizing slippage.[91–94]

Gravity influences the load of a planetary exploration rover, and load influences the sinkage. For that reason, it is important to consider the gravity of the celestial bodies, where the robot will be deployed, while analyzing tentative slip-related events.[95,96] Another variable that may impact sinkage and slippage is the speed of the vehicle. It is known that depending on the soil type (e.g. fine sand) slow velocities may lead to a higher sinkage than fast velocities.[8]

Discrete slippage estimation seems a promising research field.[41] However, there are still open questions. For example, what is the right number of discrete slip classes and what is the best machine learning algorithm in terms of accuracy, storage requirements, and computation time. Recall that a high number of intervals mean better performance from a slippage compensation standpoint but a poor performance from a slippage estimation viewpoint.[41,79] Another interesting discussion about this topic comprises the selection of supervised machine learning versus unsupervised machine learning approaches. In the context of planetary exploration robotic missions, unsupervised learning methods are preferred over supervised ones as identifying correct responses, required for training supervised methods and creating a model of the process, can be risky (e.g., high slip events) and time consuming (manual labeling from the Earth-supporting team).[97]

The velocity-based traction controllers mainly focus on increasing the input velocity (control action) of the wheels. This assumption has been demonstrated to be valid under moderate slippage on semi-compact surfaces (e.g., dry sand).[79] However, when the vehicle is moving on extremely loose conditions (e.g., snow), this solution is in fact counterproductive (i.e., increasing wheel velocity increases the sinkage rate). Future efforts must be devoted to investigating the generality of this way to proceed. Perhaps, a trade-off between torque-based and velocity-based solutions will result in the optimal traction control.

One of the key finding of this survey is that little research has been done to compensate slippage on slope traversal situations. As shown in Ref. 12, there is a critical relation between slope, slippage, and soil cohesion. More specifically, a simplified version of MSL rover (Scarecrow rover) was tested over Mars-analog terrains while considering various slopes. Results showed that slopes up to 22° were traversable on smooth bedrock and that slopes up to 28° were traversable on some cohesive soils. However, in cohesionless sand, the results showed a sharp transition between moderate slip on 10° slopes and vehicle embedding at 17°. One of the few control strategies focused on slippage compensation on slopes was presented in Ref. 82. Here, wheel driving velocity is generated by solving a system of terramechanics equations representing the force equilibrium of the robot on the slope. This optimization problem involves a comprehensive list of parameters, which are difficult to estimate in real-time (e.g., soil cohesion, friction angle, slippage, robot mass, normal load, inertia, cornering force).

Lateral or side slip constitutes another significant area for further research. This phenomenon primarily appears in steering maneuvers of ground on-road vehicles and is mainly caused by side forces (e.g., centrifugal force, cornering force), the deformation of the tire, and the conditions of the terrain (e.g., curves on a wet surface).[7,49,98] Though, planetary exploration rovers do not move at high velocities (small centrifugal force) and the deformation of the wheels is negligible (rigid wheels), lateral slip may still occur during side slope traverses.[99] Two of the few references in this context are Refs. 48,60. In the first paper, the authors present terramechanics-based models dealing with longitudinal and lateral slip. The second work introduces a method for slip angle estimation based on visually observing the traces produced by the wheels.

Another open question deals with the optimal combination of the sensor suite and the slippage estimation and compensation algorithms. As discussed along this survey, every slippage estimation and compensation method has pros and cons. Even the position of the sensors on the robot's chassis may influence the performance of the slippage detection approach as demonstrated in Ref. 41. Our recommendation is that the decision on the sensor suite and the slippage estimation and compensation algorithm must strongly depend on the features of the specific landing site and operating environment in the celestial body (e.g., terrain cohesion, lighting conditions, slopes, etc.). This means that slippage estimation and compensation strategies must be understood in terms of the whole project and not as ad hoc solutions or just as a safety layer at the bottom of the navigation architecture.

ACKNOWLEDGMENTS

The research described in this publication was carried out at the Massachusetts Institute of Technology (Cambridge, MA). Those experiments were performed at ProtoInnovations (Pittsburgh, PA). Field experiments with Fitorobot were run at the University of Almeria (Almeria, Spain). The authors thank Prof. D. Apostolopoulos for his collaboration. The authors thank four anonymous reviewers for providing very useful comments on the paper.

ORCID

Ramon Gonzalez http://orcid.org/0000-0002-3261-7991

REFERENCES

1. US National Academy of Sciences. *Vision and Voyages for Planetary Science in the Decade 2013–2022. Space Studies Board. National Research Council*; Washington, DC, USA; 2011.
2. NASA. *NASA Technology Roadmaps. TA 4: Robotics and Autonomous Systems*; Washington, DC: NASA, USA; 2015a.
3. Arvidson R, Iagnemma K, Maimone M, et al. Mars science laboratory curiosity rover megaripple crossings up to Sol 710 in Gale Crater. *J Field Robot*. 2017;34(3):495–518.
4. Chhaniyara S, Brunskill C, Yeomans B, et al. Terrain trafficability analysis and soil mechanical property identification for planetary rovers: A survey. *J Terramechan*. 2012;49(2):115–128.
5. Li R, Wu B, Di K, et al. Characterization of traverse slippage experienced by Spirit rover on Husband Hill at Gusev crater. *J Geophys Res Planets*. 2008;113(E12).
6. Wilkinson R, Behringer R, Jenkins J, Louge M, *Granular Materials and the Risks They Pose for Success on the Moon and Mars*. Presented at the AIP Conference, Salt Lake City, UT; 2005.
7. Wong JY. *Theory of Ground Vehicles*. John Wiley and Sons; Hoboken, NJ, USA; 2001.
8. Green AJ, Melzer KJ. *Performance of Boeing LRV Wheels in a Lunar Soil Simulant, Report 1, Effect of Wheel Design and Soil*. Technical Report M-71-10. Vicksburgh, MS: US Army Engineer Waterways Experiment Station. 1971.
9. Burkhalter B, Sharpe MR. Lunar roving vehicle: Historical origins, development and deployment. *J Brh Interplanet Soc*. 1995;48:199–212.
10. Spiessbach AJ. Hazard avoidance for a Mars rover. *Proc SPIE*. 1988; 1007.
11. Angelova A, Matthies L, Helmick D, Perona P. Learning and prediction of slip from visual information. *J Field Robot*. 2007;24(3):205–231.
12. Heverly M, Matthews J, Lin J, et al. Traverse performance characterization for the Mars science laboratory rover. *J Field Robot*. 2013;30(6):835–846.
13. Ding L, Gao H, Deng Z, Nagatani K, Yoshida K. Experimental study and analysis on driving wheels' performance for planetary exploration rovers moving in deformable soil. *J Terramechan*. 2011;48(1):27–45.
14. Kim SS. *The Evaluation of a Cone Penetrometer as an Index of Farm Vehicle Mobility*. PhD Thesis. Montreal, Canada: McGill University; 1969.
15. Wong JY, Reece R. Prediction of rigid wheel performance based on the analysis of soil-wheel stresses. Part I. *J Terramechan*. 1967;4(1):81–98.
16. Ono M, Fuchs TJ, Steffy A, Maimone M, Yen J. *Risk-Aware Planetary Rover Operation: Autonomous Terrain Classification and Path Planning*. Presented at the IEEE Aerospace Conference, Big Sky, MT; 2015.
17. Costes NC, Farmer JE, George EB. *Mobility Performance of the Lunar Roving Vehicle: Terrestrial Studies - Apollo 15 Results*. NASA Marshall Space Flight Center, NASA Technical Report TR R-401; 1972.
18. NASA. *Apollo 15 Mission Report. Report No. MSC-05 16 1. Manned Spacecraft Center, NASA, Houston;* 1971.
19. National Research Council, Committee on the Scientific Context for Exploration of the Moon. *The Scientific Context for Exploration of the Moon: Final Report*. Washington DC: National Academies Press; 2007.
20. Binder A. Lunar prospector: Overview. *Science*, 1998;281(5382): 1475–1476.
21. Bell JF, Squyres SW, Arvidson R, et al. Pancam multispectral imaging results from the Spirit Rover at Gusev Crater. *Science*. 2004;305(5685):800–806.
22. NASA. *NASA's Opportunity Rover Updates*. https://mars.nasa.gov/mer/mission/status_opportunityAll_2010.html. Accessed September 13, 2017.
23. Sullivan R, Arvidson R, Biesiadecki J, Bond T, Stewart H. Cohesions, friction angles, and other physical properties of martian regolith from Mars Exploration Rover wheel trenches and wheel scruffs. *J Geophys Res Planets*. 2011;116.
24. Arvidson R, Van Dyke L, Bennett K, et al. *Mars Exploration Rover Opportunity Terramechanics across Ripple Covered Bedrock in Meridiani Planum*. Paper presented at the 42nd Lunar and Planetary Science Conference, The Woodlands, TX; 2011.
25. Brooks C, Iagnemma K. Vibration-based terrain classification for planetary exploration rovers. *IEEE Trans Robot*, 2005;21(6):1185–1191.
26. Cunningham C, Nesnas I, Whittaker WL. *Terrain Traversability Prediction by Imaging Thermal Transients*. Presented at the IEEE Conference on Robotics and Automation (ICRA 2015), Seattle, WA; 2015
27. Benoit O, Gotteland P, Quibel A. Prediction of trafficability for tracked vehicle on broken soil: Real size tests. *J Terramechan*. 2003;40(2):135–160.
28. Ritcher L, Eder V, Hoheneder W, et al., *Development of a Wheeled Bevameter as a Real-Time Sensing Instrument for Robotic Vehicles*. Presented at the International Conference of International Society for Terrain-Vehicle Systems (ISTVS 2014), Seoul, Korea; 2014.
29. Barshan B, Durrant-Whyte HF. Inertial navigation systems for mobile robots. *IEEE Trans Robot Autom*. 1995;11(3):328–342.
30. Lindgren DR, Hague T, Probert Smith PJ, Marchant JA. Relating torque and slip in an odometric model for an autonomous agricultural vehicle. *Auton Robots*. 2002;13(1):73–86.
31. Ojeda L, Reina G, Borenstein J. *Experimental Results from FLEXnav: An Expert Rule-Based Dead-Reckoning System for Mars Rovers*. Presented at the IEEE Aerospace Conference, Big Sky, MT; 2004.
32. Yoshida K, Watanabe T, Mizuno N, Ishigami G. *Slip, Traction Control, and Navigation of a Lunar Rover*. Presented at the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), Nara, Japan; 2003.
33. Iagnemma K, Ward CC. Classification-based wheel slip detection and detector fusion for mobile robots on outdoor terrain. *Auton Robots*. 2009;26(1):33–46.
34. Ward C, Iagnemma K. *Classification-Based Wheel Slip Detection and Detector Fusion for Outdoor Mobile Robots*. Presented at the IEEE International Conference on Robotics and Automation, Rome. Italy; 2007.
35. Dissanayake G, Sukkarieh S, Nebot E, Durrant-Whyte H. The aiding of a low-cost strapdown measurement unit using vehicle model constraints for land vehicle applications. *IEEE Trans Robot Autom*. 2001;17(5):731–747.
36. Lamon P, Siegwart R. *3D-Odometry for Rough Terrain - Towards Real 3D Navigation*. Presented at the IEEE International Conference on Robotics and Automation (ICRA 2003), Taipei, Taiwan; 2003.
37. Ward C, Iagnemma K. A dynamic-model-based wheel slip detector for mobile robots on outdoor terrain. *IEEE Trans Robot*. 2008;24(4):821–831.
38. Helmick DM, Roumeliotis SI, Cheng Y, Clouse DS, Bajracharya M, Matthies LH. Slip-compensated path following for planetary exploration rovers. *Adv Robot*. 2006;20(11):1257–1280.

39. Yoshida K, Hamano H, Watanabe T. *Slip-Based Traction Control of a Planetary Rover*. Presented at the International Symposium on Experimental Robotics, Sant'Angelo d'Ischia, Italy; 2002.
40. Ojeda L, Cruz D, Reina G, Borenstein J. Current-based slippage detection and odometry correction for mobile robots and planetary rovers. *IEEE Trans Robot*. 2006b;22(2):366–378.
41. Gonzalez R, Apostolopoulos D, Iagnemma K. Slippage and immobilization detection for planetary exploration rovers via machine learning and proprioceptive sensing. *J Field Robot*. 2017a; https://doi.org/10.1002/rob.21736.
42. Weiss C, Frohlich H, Zell A. *Vibration-Based Terrain Classification Using Support Vector Machines*. Presented at the IEEE International Conference on Intelligent Robots and Systems, Beijing, China; 2006.
43. Weiss C, Fechner N, Stark M, Zell A, *Comparison of Different Approaches to Vibration-Based Terrain Classification*. Presented at the 3rd European Conference on Mobile Robots, Freiburg, Germany; 2007.
44. Ojeda L, Borenstein J, Witus G, Karlsen R. Terrain characterization and classification with a mobile robot. *J Field Robot*. 2006a;23(2):103–122.
45. Wang S, Kodagoda S, Wang Z, Dissanayake G. *Multiple Sensor Based Terrain Classification*. Australasian Conference on Robotics and Automation, Melbourne, Australia; 2011.
46. Brooks C, Iagnemma K. Self-supervised terrain classification for planetary surface exploration rovers. *J Field Robot*. 2012;29(3):445–468.
47. Yen J. Slip validation and prediction for Mars exploration rovers. *Sens Transduc J*. 2008;90:233–242.
48. Ishigami G, Miwa A, Nagatani K, Yoshida K. Terramechanics-based model for steering maneuver of planetary exploration rovers on loose soil. *J Field Robot*. 2007;24(3):233–250.
49. Lenain R, Thuilot B, Cariou C, Martinet P. *Adaptive Control for Car Like Vehicles Guidance Relying on RTK GPS: Rejection of Sliding Effects in Agricultural Applications*. Presented at the IEEE International Conference on Robotics and Automation, Taipei, Taiwan; 2003.
50. Low CB, Wang D. GPS-based path following control for a car-like wheeled mobile robot with skidding and slipping. *IEEE Trans Control Syst Technol*. 2008;16(2):340–347.
51. Tham YK, Wang H, Teoh EK. Multi-sensor fusion for steerable four-wheeled industrial vehicles. *Control Eng Pract*. 1999;7(10):1233–1248.
52. Olson E. *AprilTag: A Robust and Flexible Visual Fiducial System*. Presented at the IEEE International Conference on Robotics and Automation, Shanghai, China; 2011.
53. Gonzalez R, Rodriguez F, Guzman JL. *Autonomous Tracked Robots in Planar Off-Road Conditions*. Springer, Berlin, Germany; 2014.
54. Maimone M, Cheng Y, Matthies L. Two years of visual odometry on the Mars Exploration Rovers. *J Field Robot*. 2007;24(3):169–186.
55. Matthies L, Maimone M, Johnson A, et al. Computer vision on Mars. *Int J Comput Vis*. 2007;75(1):67–92.
56. Wellington C, Stentz A. *Online Adaptive Rough-Terrain Navigation Vegetation*. Presented at the IEEE International Conference on Robotics and Automation, New Orleans, LA; 2004.
57. Howard TM, Morfopoulos A, Morrison J, et al. *Enabling Continuous Planetary Rover Navigation Through FPGA Stereo and Visual Odometry*. Presented at the IEEE Aerospace Conference, Big Sky, MT; 2012.
58. Johnson AE, Goldberg SB, Cheng Y, Matthies LH, *Robust and Efficient Stereo Feature Tracking for Visual Odometry*. Presented at the IEEE International Conference on Robotics and Automation, Pasadena, CA; 2008.
59. Otsu K, Otsuki M, Ishigami G, Kubota T. *Advanced Visual Odometry for Planetary Exploration Rover*. Presented at the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), Turin. Italy; 2012.
60. Reina G, Ishigami G, Nagatani K, Yoshida K. Odometry correction using visual slip angle estimation for planetary exploration rovers. *Adv Robot*. 2010;24(3):359–385.
61. Gonzalez R, Rodriguez F, Guzman JL, Pradalier C, Siegwart R. Combined visual odometry and visual compass for off-road mobile robots localization. *Robotica*. 2012;30(6):865–878.
62. Gonzalez R, Rituerto A, Guerrero JJ. Improving robot mobility by combining downward-looking and frontal cameras. *Robotics*. 2016b;5(4):1–19.
63. Nagatani K, Ikeda A, Ishigami G, Yoshida K, Nagai I. Development of a visual odometry system for a wheeled robot on loose soil using a telecentric camera. *Adv Robotics*. 2010;24(8-9):1149–1167.
64. Pertile M, Chiodini S, Debei S. *Comparison of Visual Odometry Systems Suitable for Planetary Exploration*. Presented at the IEEE Metrology for Aerospace (MetroAeroSpace), Benevento, Italy; 2014.
65. Brunner C, Peynot T, Vidal-Calleja T, Underwood J. Selective combination of visual and thermal imaging for resilient localization in adverse conditions: Day and night smoke and fire. *J Field Robot*. 2013;30(4):641–666.
66. Gonzalez R, Lopez A, Iagnemma K. Thermal vision, moisture content, and vegetation in the context of off-road mobile robots. *J Terramechan*. 2017b;70 (April):35–48.
67. Ishigami G, Otsuki M, Kubota T. *Lidar-Based Terrain Mapping and Navigation for a Planetary Exploration Rover*. Presented at the Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS); 2012.
68. Shaukat A, Blacker P, Spiteri C, Yang G. Towards camera-LIDAR fusion-based terrain modelling for planetary surfaces: Review and analysis. *Sensors*. 2016;16(11):1–24.
69. Ulsoy AG, Peng H, Cakmakci M, *Automotive Control Systems*. Cambridge University Press; 2012.
70. Iagnemma K, Dubowsky S. *Mobile robots in rough terrain. Estimation, motion planning, and control with application to planetary rovers. Springer Tracts in Advanced Robotics*. Germany: Springer; 2004.
71. Krebs A, Thueer T, Carrasco E, Siegwart R. *Towards Torque Control of the CRAB Rover*. Presented at the International Symposium on Artificial Intelligence, Robotics and Automation in Space, Los Angeles; 2008.
72. Balakrishna R, Ghosal A. Modeling of slip for wheeled mobile robots. *IEEE Trans Robot Autom*. 1995;11(1):126–132.
73. Reina G, Ojeda L, Milella A, Borenstein J. Wheel slippage and sinkage detection for planetary rovers. *IEEE/ASME Trans Mechatron*. 2006;11(2):185–195.
74. Higa S, Nagaoka K, Nagatani K, Yoshida K. Measurement and modeling for two-dimensional normal stress distribution of wheel on loose soil. *J. Terramechan*. 2015;62:63–73.
75. Meirion-Griffith G, Spenko M. A modified pressure–sinkage model for small, rigid wheels on deformable terrains. *J Terramechan*. 2011;48(2):149–155.
76. Meirion-Griffith G, Spenko M. A pressure-sinkage model for small-diameter wheels on compactive, deformable terrain. *J Terramechan*. 2013;50(1):37–44.
77. Baumgartner ET, Aghazarian H, Trebi-Ollennu A, Huntsberger TL, Garrett MS. *State Estimation and Vehicle Localization for the FIDO Rover*. Paper presented at the Proceedings of SPIE - The International Society for Optical Engineering, Boston, MA; 2000.

78. Peynot T, Lacroix S. *Enhanced Locomotion Control for a Planetary Rover*. Presented at the IEEE International Conference on Intelligent Robots and Systems, Las Vegas, NV; 2003.

79. Gonzalez R, Iagnemma K. *Soil Embedding Avoidance for Planetary Exploration Rovers*. Presented at the International Conference of International Society for Terrain-Vehicle Systems (ISTVS 2016), Detroit, MI; 2016a.

80. Carlone TJ, Anderson JJ, Amato JL, Dimitrov VD, Padir T. *Kinematic Control of a Planetary Exploration Rover over Rough Terrain*. Presented at the IEEE International Conference on Systems, Man, and Cybernetics, Manchester, UK; 2013.

81. Reina G. Cross-coupled control for all-terrain rovers. *Sensors*. 2013;13(1):785–800.

82. Ishigami G, Nagatani K, Yoshida K. Slope traversal controls for planetary exploration rover on Sandy terrain. *J Field Robot*. 2009;26(3):264–286.

83. Klancar G, Skrjanc I. Tracking-error model-based predictive control for mobile robots in real time. *Robot Auton Syst*. 2007;55(6):460–469.

84. Christensen P, Jakosky B, Kieffer H, Malin M, McSween H, Nealson K. The thermal emission imaging system (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci Rev*. 2004;110(1):85–130.

85. Biccari D, Picardi G, Seu R. *Mars High Resolution Shallow Radar (SHARAD) for the MRO 2005 Mission*. Presented at the IEEE International Geoscience and Remote Sensing Symposium, Toronto, Ontario, Canada; 2002.

86. Brooker G, Johnson D, Underwood J, Martinez J, Xuan L. Using the polarization of millimeter-wave radar as a navigation aid. *J Field Robot*. 2015;32(1):3–19.

87. Milella A, Reina G. A self-learning framework for statistical ground classification using radar and monocular vision. *J Field Robot*. 2015;32(1):20–41.

88. Creager C, Johnson K, Plant M, Moreland S, Skonieczny K. Push–pull locomotion for vehicle extrication. *J Terramechan*. 2015;57:71–80.

89. Lauria M, Conti F, Maeusli PA, Van Winnendael M, Bertrand R, Siegwart R. *Design and Control of an Innovative Micro-Rover*. Presented at the Proceedings of the Fifth ESA Workshop on Advanced Space Technologies for Robotics and Automation, The Netherlands; 1998.

90. Siegwart R, Lamon P, Estier T, Lauria M, Piguet R. Innovative design for wheeled locomotion in rough terrain. *Robot Auton Syst*. 2002;40(2-3):151–162.

91. Ding L, Deng Z, Gao H, Nagatani K, Yoshida K. Planetary rovers' wheel–soil interaction mechanics: New challenges and applications for wheeled mobile robots. *Intell ServRobot*. 2011;4(1):17–38.

92. Higa S, Sawada K, Nagaoka K, Nagatani K, Yoshida K. *Measurement of Stress Distributions of a Wheel with Grousers Traveling on Loose Soil*. Presented at the IEEE International Conference on Robotics and Automation (ICRA 2016), Stockholm, Sweden; 2016.

93. Sutoh M, Nagaoka K, Nagatani K, Yoshida K. Design of wheels with grousers for planetary rovers traveling over loose soil. *J Terramechan*. 2013;50(5-6):345–353.

94. Xiao W, Zhang Y. Design of manned lunar rover wheels and improvement in soil mechanics formulas for elastic wheels in consideration of deformation. *J Terramechan*. 2016;65 (June):61–71.

95. Bui HH, Kobayashi T, Fukagawa R, Wells JC. Numerical and experimental studies of gravity effect on the mechanism of lunar excavations. *J Terramechan*. 2009;46(3):115–124.

96. Wong JY. Predicting the performances of rigid rover wheels on extraterrestrial surfaces based on test results obtained on Earth. *J Terramechan*. 2012;49(1):49–61.

97. Bouguelia MR, Gonzalez R, Iagnemma K, Byttner S. Unsupervised classification of slip events for planetary exploration rovers. *J Terramechan*, In Press. 2017. https://doi.org/10.1016/j.jterra.2017.09.001

98. Cariou C, Lenain R, Thuilot B, Berducat M. Automatic guidance of a four-wheel-steering mobile robot for accurate field operations. *J Field Robot*. 2009;26(6-7):504–518.

99. Inotsume H, Sutoh M, Nagaoka K, Nagatani K, Yoshida K. *Evaluation of the Reconfiguration Effects of Planetary Rovers on their Lateral Traversing of Sandy Slopes*. Presented at the IEEE International Conference on Robotics and Automation, Saint Paul, MN; 2012.

100. Webster G, Brown D. *Now a Stationary Research Platform, NASA's Mars Rover Spirit Starts a New Chapter in Red Planet Scientific Studies*. http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20100126a.html; 2010. Accessed September 13, 2017.

101. Young K. *Mars Rover Escapes from the "Bay of Lamentation."* https://www.newscientist.com/article/dn9286-mars-rover-escapes-from-the-bay-of-lamentation/; 2006. Accessed September 13, 2017.

102. Wilcox B, Nguyen T. *Sojourner on Mars and Lessons Learned for Future Planetary Rovers*. Presented at the SAE International Conference on Environmental Systems, Danvers, MA; 1998.

103. Carrier D. *Soviet Rover Systems*. Presented at the Space Programs and Technology Conference, Huntsville, AL; 1992.

104. Grotzinger JP, Crisp J, Vasavada AR, et al. Mars science laboratory mission and science investigation. *Space Sci Rev*. 2012;170(5):5–56.

105. Lakdawalla E. *Curiosity Update, Sols 671–696: Out of the Landing Ellipse, into Ripples and Pointy Rocks*. www.planetary.org/blogs/emily-lakdawalla/2014/07241401-curiosity-update-sols-671-696.html; 2017. Accessed September 13, 2017.

106. NASA. 2015b. *NASA's Curiosity Rover Adjusts Route Up Martian Mountain*. http://www.jpl.nasa.gov/news/news.php?feature = 4596. Accessed September 13, 2017.

How to cite this article: Gonzalez R, Iagnemma K. Slippage estimation and compensation for planetary exploration rovers. State of the art and future challenges. *J Field Robotics*. 2018;35:564–577. https://doi.org/10.1002/rob.21761