Taxonomy, Systems Review and Performance Metrics of Planetary Exploration Rovers

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***Abstract*— A taxonomy of planetary exploration rovers is presented, followed by a review of systems used in missions and in an experimental phase. The baseline design emerges as four or six wheels, rocker-bogie based passive suspension and all wheel driving / selected wheel steering. A trend is also apparent in the use of wheel - legged hybrid locomotion. The performance metrics are presented by which the differing configurations of the locomotion subsystem for wheeled rovers with a passive suspension may be systematically evaluated. The taxonomy and aggregated metrics presented in this paper aid in the comparison and selection of rover characteristics, while the baseline design is a representative example of current practices and future trends.**

***Keywords*— space, rover, robotic exploration, locomotion, suspension, mobility, rocker-bogie, taxonomy, performance, metrics**

I. INTRODUCTION

The autonomous robotic exploration of Mars, the Moon, asteroids and other celestial bodies is a necessary step for space exploration and the expansion of human presence in space. These exploration robots can take the form of rovers, stationary landers, hoppers and probes [1]. The term rovers usually applies to systems that employ wheels for locomotion; however they may alternatively use tracks, legs or a combination of these. In relative terms, the most mature locomotion method is wheeled, whereas legged and tracked locomotion are still in an experimental phase for space applications [1, 2]. The focus then is on wheeled rovers, as these have demonstrated their ability to perform autonomously in a robust and reliable manner and do not have the control complexity and power distribution issues associated with legged and tracked vehicles.

Landers, such as NASA's Viking Landers on Mars (1975) [3] and the Phoenix Mars Lander (2008) [4], are stationary and their exploration capabilities are limited to the landing site. Hoppers and probes have been used in asteroid landing and sample collection, for example in JAXA's Hayabusa mission (2003) [5], the joint NASA, ESA and ASI Cassini-Huygens mission (1997) [6] and ESA'S Rosetta mission (2004) [7].

Rovers have significant advantages: they can traverse different terrain types, slopes and overcome obstacles and so they can explore a large area. The first planetary vehicles were the Apollo Lunar Roving Vehicles (1971, 1972) and the first teleoperated rovers were the Lunokhod rovers (1971, 1973) [1]. Since then, research efforts have mostly focused on developing wheeled rovers for Mars exploration, as evidenced by NASA's Sojourner rover (1996) [8], Spirit and Opportunity (2003) [9], and Curiosity (2011) [10]. Future Mars missions include ESA's ExoMars rover (2018) [11] and NASA's Mars 2020 Rover [12]. In December 2013, China landed the rover Yutu ("Jade Rabbit") on the Moon [13], the first since the Lunokhod rovers.

The main function of an exploration rover is to fulfill its scientific objectives: exploration, terrain mapping, in-situ surface analysis, soil sample collection. This is the concept of the "robotic field geologist": a rover is used instead of an astronaut team for performing science observations [9]. The rover has to move through a challenging, unknown and varied terrain (loose sand, hard soil, rocks, slopes). The configuration and performance of the locomotion subsystem, consisting of the wheels or an alternative locomotion method, the suspension and the actuation, is essential for the overall success. A question arises as to how we can categorize and compare the different types and configurations of the locomotion subsystem and what is the current state of the art.

In this paper, the taxonomy and the current status of planetary exploration rovers are reviewed. The review includes systems used in missions and selected experimental designs. From this review, a baseline design emerged. Metrics are then discussed, to systematically compare the performance of different locomotion configurations for wheeled rovers with passive suspension. Application examples and the limitations when using these metrics are also discussed. The taxonomy and aggregated metrics can be used for comparing rover characteristics from a set of possible configurations, thus facilitating a more systematic design process. The taxonomy and review highlight the current configurations and state of the art of planetary rovers. The baseline design incorporates current practices and future trends and can be used as a starting point when designing and comparing new configurations.

II. TAXONOMY OF PLANETARY EXPLORATION ROVERS

An exploration rover consists of the following subsystems: (a) instrumentation, (b) communications, (c) on board data handling (OBDH), (d) guidance, navigation and control (GNC), (e) power, (f) thermal, (g) chassis & structures (e.g. camera mast, arm), (h) locomotion incl. the suspension [14]. The locomotion subsystem must reliably transport the rover across the terrain, execute real-time motion control maneuvers and work harmoniously with the other subsystems. The suspension must maintain the rover's stability by reducing the effects of dynamical loads and impulse forces from driving and overcome obstacles up to a certain size when needed. The chassis provides the structural support and must be able to support the suspension and withstand the forces applied to it. To show the configurations and the variety of possible designs, a taxonomy of exploration rovers [15] is presented in Table I with regards to locomotion method (mobility type), chassis articulation, suspension type and steering system configuration.

The configuration of the suspension is important for wheeled rovers. For legged locomotion, the system uses the legs to walk, so the legs actively stabilize it. The movement is discreet as the legs travel using only the contact points between the bottom of the leg and the ground.

A passive suspension uses springs and dampers with a predefined damping ratio to absorb the dynamical loads whereas a semi-active suspension has a controllable damper [16]. An active suspension also uses springs and dampers and a powered actuator is added to actively control the damping ratio. In terms of performance, response time and reduction of impulse forces, active suspensions are superior, however they are costly, complex and require a dedicated power supply [16]. A further distinction is made between kinematic and dynamic suspensions [17]. Dynamic suspensions use springs, torsion tubes, dampers and high speed actuators to adjust the damping ratio. These are used when a fast response to comply with the terrain is needed. Kinematic suspensions use freely pivoting joints with unsprung and undamped passive linkages; they are common in slow-moving vehicles. The speed of a planetary rover is low, usually less than 5cm/s, and operates in a low gravity environment. The forces applied on it during its movement are slowly evolving and a quasi-static operation can be assumed, so a kinematic suspension is suitable [17].

The suspension often used for a planetary exploration rover is the rocker-bogie six wheel mobility system (Fig. 1).

TABLE I. PLANETARY EXPLORATION ROVER TAXONOMY

Criterion	*Type*	*Example*
Mobility Type	Continuous	Wheeled Tracked Crawling Tumbling
	Discrete	Legged (two or more legs) Jumping (one or more legs)
	Hybrids	Wheels on legs Tracks and wheels Circulating wheels
Chassis	Articulation	Articulated (active /passive control) Fixed
Suspension	Active Semi-Active	Independent Dynamic
	Passive	Rocker-Bogie Multiple Rockers/ Multiple Bogies Independent Kinematic
Steering configuration	Wheeled locomotion	Skid Articulated Coordinated (e.g. Ackerman steering) Independent (incl. crab steering)

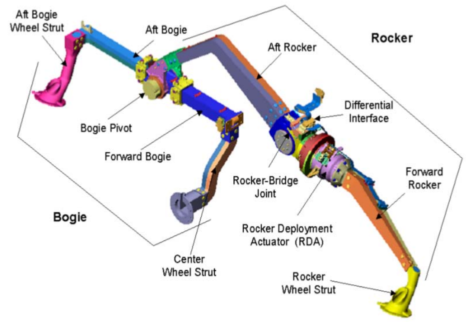

Figure 1. Rocker-Bogie Suspension [18]

The rocker-bogie suspension is a passive kinematic suspension that along with a differential keeps all wheels in contact with the surface at all times. This has two advantages [18]. Firstly, independent of the rover's pose, the pressure on the ground from each wheel is equal for all so no wheel sinks more than the rest. This equilibration of pressure is very important for soft terrain because it ensures that the rover will not sink in the ground. Secondly, when climbing all wheels remain in contact with the ground and are under load, which helps the rover to ascend. The suspension can absorb significant driving loads and is soft enough to limit the accelerations on the body but has enough stiffness so that no overly large deflections occur [18].

The two main components are the rocker and bogie, connected via a free rotating pivot, called the bogie pivot. The right and left sets of the rocker-bogie assemblies are also connected to each other via the differential, a passive, motion-reversal joint that constrains the two sides to equal and opposite motion and keeps the rover level by maintaining the average pitch angle of both rockers. The rocker-bogie suspension allows the traversing of obstacles with a size of at least a wheel diameter [18]. A variation is the three bogie system used in the ExoMars rover; there are two longitudinal side bogies and one traverse bogie, without a differential linkage [11]. The ability of the rocker-bogie suspension to maintain the average pitch angle between the two sides is called body averaging and can be adapted for four wheels by using a rocker and a pivoting joint for each side, connected with a differential or a linkage mechanism. Body averaging is the more general case in which the two chassis sides are connected via a joint or a linkage (active or passive) to maintain the average pitch between them.

An important design aspect is the steering configuration. For planetary exploration rovers, usually all wheels are driven and at least some of them are steered. In independent (or explicit) steering each wheel is driven and steered with a dedicated motor assembly; this increases the ability of the rover to maneuver and reduces the turning radius to zero, but also increases the overall complexity [19]. When each wheel is steered, crab steering is achieved: all wheels point at the same direction by the same angle and the rover can move sideways. In skid steering, each set of wheels at the left and right side of the rover is independently powered and a zero turn radius is possible. However, skidding requires more power and imposes considerable stress on the chassis and on the wheels [19]. Skid steering is also used for tracked rovers, where each track is driven separately.

The number of wheels is also important and the choice is driven by the mission requirements and the chassis, suspension and steering system design. The number of wheels is usually four or six. Eight or more wheels are cumbersome and difficult to control. Six wheels are generally better for traversing obstacles, reducing the pressure at each wheel and maintaining a smooth chassis pitch adjustment, whereas four wheels have reduced motion resistance, power requirements and complexity and can be actuated with as little as two motors [20].

III. Review of Planetary Exploration Rovers

A review of the planetary exploration rovers successfully used (Table II) and selected experimental designs (Table III), focusing on wheeled, legged or hybrid systems, is presented to provide an overview of ongoing research and to highlight the different configurations (Table I). The maximum speed, obstacle and tilt (Tables II, III) may be exceeded in some cases (e.g. level hard ground with high traction).

TABLE II. Planetary Exploration Rovers

Name (Launch)	*Body*	*Weight (on Earth) Size*	*Locomotion*	*Suspension*	*Speed*	*Obstacle (max) Tilt (max)*
Apollo LRV [21] (1971, 1972)	Moon	210 kg (vehicle) 490 kg (payload on Moon) 1.14(h)x1.83(w)x3.1(l) (m)	4 wheels, Ø51cm Double Ackerman Aluminium, titanium	Passive: parallel triangular suspension arms, torsion bars	250 – 360 cm/s (max)	30 cm 23 deg
Lunokhod [1] (1971, 1973)	Moon	840 kg 1.35(h)x1.6(w)x1.7(l) (m)	8 wheels, Ø51cm Skid steering	Passive: independent at each wheel	27.8 cm/s 55.5 cm/s	n/a
Sojourner [8] (1996)	Mars	10.6 kg (rover) 5 kg (instruments) 0.3(h)x0.48(w)x0.65(l) (m)	6 wheels, Ø13cm 6 drive, 4 steer Aluminium, rigid, grousers	Rocker-Bogie	1 cm/s (max) 0.67 cm/s (av.)	13 cm 15 deg
Spirit & Opportunity [9] (2003)	Mars	176.5 kg 1.5(h)x1.2(w)x1.4(l) (m)	6 wheels, Ø25cm 6 drive, 4 steer Aluminium, rigid, grousers	Rocker-Bogie	4.6 cm/s (max) 1 cm/s (av.)	25 cm 16 deg
Curiosity [10] (2011)	Mars	900 kg 2.2(h)x2.8(w)x2.8(l) (m)	6 wheels, Ø50cm 6 drive, 4 steer Aluminium, rigid, grousers	Rocker-Bogie	4.6 cm/s (max) 1 cm/s (av.)	50 cm 28 deg
Yutu [13] (2013)	Moon	120 kg 20 kg (payload)	6 wheels 6 drive, 4 steer Aluminium, rigid, grousers	Rocker-Bogie	n/a	n/a
ExoMars [11, 22] (2018)	Mars	310 kg 2(h)x1.1(w)x1.2(l) (m)	6 wheels, Ø25 cm 6 drive, 6 steer wheel-walking Aluminium, flexible, grousers	Three bogies	3.6 cm/s (max)	25 cm 40 deg

TABLE III. Experimental Designs for Planetary Exploration

Name (Developer)	*Body*	*Weight (on Earth) Size*	*Locomotion*	*Suspension*	*Speed*
SR-II [20] (University of Oklahoma)	Mars	22.07 kg 0.4(h)x0.36(w)x0.84(l) (m)	4 wheels, Ø21 cm 4 wheel drive, skid steer Aluminum, grousers	Passive (Kinematic) Body averaging with a geared differential	10.2 cm/s (av.)
Scarab [15, 17] (Carnegie Mellon University)	Moon	28 kg 0.8 – 1.4 (m) variable wheelbase 1.2 m nominal wheelbase	4 wheels, Ø71 cm 4 wheel drive, Skid-steering Commercial skid loader tires or experimental lunar wheels	Passive, kinematic: rocker on each side, connected via a linkage Active body roll control	3-6 cm/s (max)
NOMAD [23] (Carnegie Mellon University)	Moon, Artic Exloration	725 kg 2.4(h) x 2.4(w) x 2.4(l) (m) fully deployed 1.8(w) x 1.8(l) (m) stowed configuration	4 wheels, Ø76 cm 4 wheel drive Skid steering, double Ackerman, point turning Aluminium, grousers	Passive: two bogies connected via an averaging linkage Active: transforming chassis via a pair of four-bar mechanisms	50 cm/s (max) 30 cm/s (av.)
Micro 5 [24] (JAXA)	Moon	30 kg 0.6(h)x0.85(w)x0.85(l) (m)	5 wheels, Ø15 cm 5 wheel drive, 4 steer Aluminum, rigid, grousers	Passive, uses the PEGASUS system	3cm/s
Chariot (NASA) [25, 26]	Moon	2000 kg 3(h)x4(w)x4.5(l) (m)	6 pairs of wheels, Ø 68 cm Independent wheel steering Commercial pneumatic tyres	Active and Passive Suspension in series, at each wheel	20 km/hr (max) (555 cm/s)
ATHLETE (NASA) [27]	Moon	300 kg (payload) 4(h)x2.75(w)x2.75(l) (m)	Hybrid legs / wheels Ø71 cm 6 DOF legs Independent wheel actuation Commercial pneumatic tyres	n/a	3km/h (max) (83 cm/s)
Crawler [28] (DLR)	Planetary	3.5 kg Feet span: 0.35 x 0.35 (m) Height: 0.01 – 0.12 (m)	Legged, 6 legs each with 4 DOF, 3 actively controlled	n/a	20 cm/s (max)
SpaceClimber [29] (DFKI)	Planetary	23 kg 0.17(h)x0.2(w)x0.85(l) (m)	Legged 6 legs, 4 active DOF each	n/a	17.5 cm/s (max)
Nanokhod [30] (ESA)	Moon, Mars, Mercury	3 kg 0.65(h)x0.16(w)x0.24(l) (m)	Two track units Skid steering	n/a	0.14 cm/s (av.)
CESAR [31] (University of Bremen)	Moon	13.3 kg 0.5(h)x0.82(w)x0.98(l) (m)	Hybrid: two wheels / legs	n/a	n/a

A. *Flown planetary rovers.*

The Apollo LRV were operated by astronauts and the Lunokhods were teleoperated; Earth operators sent driving commands in real time. All other rovers have autonomous navigation capabilities: Earth operators upload instructions for the rover to follow and the rover can also plot its own path and place its instruments on a selected target using the on-board navigation software [32]. All rovers use solar panels, except Curiosity which uses a radioisotope thermoelectric generator (RTG), and the Apollo LRV, which used non rechargeable batteries. NASA's Mars 2020 rover [12] is based on Curiosity, with upgraded hardware and new scientific instruments. The size will be approximately 2.2(h) x 2.7(w) x 3(l) (m). Further details are under consideration and so it is not included.

B. *Experimental designs.*

The SR-II rover uses two motors with a drive train through a hollow tubular suspension to reduce complexity and power consumption. This design ensures ground contact and even pressure for all four wheels. SCARAB combines a passive rocker suspension for pitch adjustment with an active part for chassis transforming. An actuator is placed at each rocker joint for adjusting the sweep angle to change the height independently at each side and for expanding the wheelbase. NOMAD also has a transforming chassis via a pair of four-bar mechanisms to achieve two configurations: stowing and driving. JAXA's Pegasus suspension consists of a 4 wheel drive system and a 5th wheel attached to a link. The link is connected to the chassis with a passive joint and steering is achieved via a differential. This configuration equilibrates the load on all wheels when climbing and is simpler and more suitable for a small rover. Chariot was designed to be used by astronauts and also as an unmanned payload carrier. The active suspension levels and adjusts the chassis' height. ATHLETE is a hexagonal platform on six legs designed for carrying cargo. Each leg has a wheel at its end and the system uses the wheels to roll over stable, flat ground and the legs, with the locked wheels as "feet", for challenging terrain. Crawler and Space Climber are designed as small scouts for craters. The Nanokhod rover is a small explorer tethered to a lander that provides power and communications. CESAR was developed for an ESA lunar crater robotic exploration challenge. The wheel/leg hybrid consists of a central plate cut out of polyoxymethylene, to which five flexible spokes of the same material are attached. The central plate is driven by a motor and each spoke acts as a grouser as well as the "foot" of a leg.

C. *Discussion: Common themes and future trends*

There are several designs for planetary rovers; however, all rovers used in a mission since Sojourner share a similar design: six wheels, rocker-bogie suspension, independent all wheel driving and selected wheel steering. The main difference is the weight, size and power requirements. With each successive mission and as technology and launch capabilities advance, the scale and demands of the objectives are increased as well as the system's autonomous navigation capability [32].

From Tables II and III a baseline design emerges: (a) wheeled locomotion using four to six rigid wheels (b) all wheel drive and selected wheel steering, (c) passive kinematic suspension, usually with a differential for steering. Currently, the preferred suspension is the rocker-bogie; nonetheless, the experimental systems exhibit a wider range of designs.

Wheeled locomotion is technologically mature, energy efficient and less complex than legged or tracked, however wheels perform well in average to moderate terrain whereas legs perform better overall, with the cost of increased control and power distribution requirements [15]. Tracks perform better on soft terrain than wheels but have reliability issues and a high power-to-weight ratio [15, 33]. Therefore, wheels are the best overall solution. A trend however is apparent in using hybrid wheel / legged locomotion combining the maturity of wheels with the versatility of legs, as seen in ATHLETE, CESAR and ExoMars. ATHLETE's hybrid locomotion ensures that in difficult terrain it can lift one leg at a time, walk out and then use its wheels. As the system uses its legs in difficult terrain, the wheels and their actuators are sized for nominal terrain, which requires less torque and a smaller wheel diameter. This results in a mass saving of up to 25% [34]. Of the eight robots in the ESA challenge, CESAR was the only one that completed the mission. The other robots included wheeled, tracked and track / wheel hybrids. The ExoMars rover is notable as it is currently the only mission-ready system that uses hybrid locomotion. Using a passive suspension reduces complexity and increases reliability: fewer actuators and fewer moving parts reduce the chance of mechanical failure and the control requirements. A kinematic suspension has the benefits of simplicity, stiffness and a more equal distribution of weight by the linkages, such as in the case of the rocker-bogie suspension [15, 17, 18]. The NASA Chariot system is designed to be used by astronauts and it is therefore the only design that uses an active suspension to ensure the system's stability and to reduce the effects of dynamical loads to a level suitable for human usage. Otherwise, when active elements are used it is for adjusting the chassis and shifting the centre of gravity, so that the system can lean, re-stabilize and raise itself.

The main step forward is the ExoMars rover which combines novel characteristics not previously used in a Mars rover [35], as can be seen from Table II: (a) all wheel driving and steering, (b) flexible wheels, (c) three boogie suspension without a differential (d) wheel – walking. The suspension consists of two longitudinal side bogies and one traverse bogie and the wheels are coupled in pairs at each bogie. This design has the same mobility performance with the rocker-bogie but since it does not use a differential it is simpler, lighter with a reduced stowage volume [35]. The flexible wheels with grousers increase the traction and therefore the slope and obstacle traverse capability [35, 36]. The six wheel driving, steering and wheel walking design requires 18 motors: each wheel has one motor for driving, one for steering and one for walking. When wheel-walking, each wheel is independently moved forwards or backwards so that the rover can slowly walk out of adverse terrain and also adjust its attitude and ground clearance. In turn, this increases the overall stability and ability to negotiate soft terrain and steep slopes [35].

IV. PEFORMANCE METRICS FOR WHEELED LOCOMOTION

It is necessary to define metrics to evaluate and compare consistently and systematically the performance of differing designs. Metrics are qualitative or quantitative and are categorized as performance, locomotion mode and operational. Performance metrics apply to systems under development and measure the mobility capability of the locomotion subsystem; [37] and [38] define metrics for wheeled rovers and [39] for legged robots. Locomotion mode metrics compare the performance between different locomotion types; [31] has a qualitative comparison between wheels, legs and tracks and [33] has a comparison between tracks and wheels. Operational metrics measure the required performance vs. actual in the field [40]. Metrics that evaluate the autonomy have also been proposed, such as [41]. The focus is on performance metrics for evaluating the locomotion subsystem of the baseline design previously identified: wheels and passive suspension.

A. Performance metrics for wheeled locomotion

The locomotion subsystem must perform the following tasks [37]: (a) trafficability: generate traction to drive the rover through varied terrain and overcome motion resistance, (b) maneuverability: navigate and change heading via steering, (c) terrainability: negotiate rough terrain (slopes, obstacles) without loss of forward progress and stability. The degree by which the rover's locomotion is successful in these tasks is influenced by these parameters: number and type of wheels (diameter, width, flexibility, grousers), suspension geometry, chassis articulation, steering method. The performance metrics examine how different configurations influence these tasks. For each task a set of configuration equations were defined in [37] to provide an analytical framework for the synthesis of locomotion subsystems. Each equation can be independently solved for an in-depth evaluation of the relationship between the configuration parameters and the rover's performance. The configuration equations include the influence of terrain characteristics (e.g. soil type), locomotion parameters (e.g. steering type) and performance parameters (e.g. maximum slope, maximum available torque). The indices examined are:

- Trafficability: wheel sinkage, soil thrust & traction, motion resistance, drawbar pull (difference between traction and motion resistance), drive torque & power.
- Maneuverability: steering scheme, motion resistance and traction when steering.
- Terrainability: static stability, slope traverse.

Reference [38] further expands the terrainability metrics and a new metric is introduced, the velocity constraint violation. This metric compares suspensions by the slip they cause in uneven terrain due to kinematic constraints that result to a deviation from the ideal velocity; the velocity at which no slip occurs. On a level plane in theory all wheels have the same speed and no slip occurs. In practice, slip remains low because all wheel velocities are almost equal. In rough terrain, kinematic constraints require every wheel to rotate at individual speeds and slip increases. It is desirable to use a suspension that complies well with the kinematic constraints [38].

B. Applications and limitations of performance metrics

The metrics defined in [37] were applied to the design of NOMAD (Table III), to produce a rover with skid steering and a transforming chassis capable of traversing a Moon or Mars analogue terrain. The metrics defined in [38] were developed as part of the selection of the locomotion subsystem for the ExoMars rover. Six different suspension designs were proposed, all using a passive suspension based on the rocker-bogie configuration and six wheels [35, 36]. It was necessary to systematically compare their mobility performance to achieve an optimized suspension configuration capable of fulfilling the predefined criteria: fixed volume (stowage restriction), mass, static stability, obstacle height, slope traverse [35] (Table II). The metrics were used to quantify each design's performance and then to compare them, using the following methodology [38]: comparison using simulation and then experimental verification of the results using a hardware model of each design. The three boogie suspension emerged as the most capable of fulfilling the aforementioned criteria. The issue of rigid vs. flexible wheels was also investigated using performance metrics as defined in [37, 38] (motion resistance, drawbar pull, peak torque and power) to examine the wheel performance [35]; a flexible wheel with grousers was selected. Having selected a suspension and wheel design, the issue of wheel walking was examined as to whether it would improve the overall locomotion performance [35]. This systematic comparison resulted in a Mars rover design with augmented capabilities, as discussed in the previous section.

However, performance metrics have some limitations. The metrics used are not dimensionless and when comparing the performance of designs with different chassis sizes, a normalization process is required for a meaningful comparison. This is not always possible since the chassis size is often driven by other factors: stowage volume, payload requirements. The metrics are influenced by more than one parameter and the normalization process might inadvertently remove some of that influence. Defining a platform of fixed size is recommended before examining the configuration of the locomotion subsystem [38]. Sufficient knowledge of the terrain properties is required and when in doubt, it is recommended that worst case conditions and a stochastic model are utilized [37].

V. CONCLUSIONS

Planetary exploration rovers have increased exploration capabilities and must move through an unknown and challenging terrain to meet their scientific objectives. The locomotion subsystem propels the rover across the terrain, so its performance is critical. There are several configurations for the locomotion subsystem and a taxonomy is proposed to highlight them. The review of systems successfully used in a mission and selected experimental systems provides an overview of current research and of locomotion configurations. From this review emerged: (a) a baseline design: four or six wheels and passive kinematic suspension, (b) a trend in using wheel / legged hybrid locomotion, (c) the ExoMars rover utilizes novel characteristics including wheel-walking. Hybrid wheel / legged locomotion combines the maturity, reliability and good performance of wheels in average to moderate terrain with the performance of legs on rugged terrain. For the ATHLETE design, this allowed the sizing of the wheels and their actuators for nominal terrain. For ExoMars, wheel-walking improves the stability and ability to negotiate soft terrain and steep slopes. Each new design must consider different locomotion configurations and select an optimized set to satisfy the mission requirements. This necessitates the use of performance metrics for evaluating the performance of the locomotion subsystem and selecting a configuration. The ExoMars rover was designed by utilizing performance metrics to choose an optimum configuration with novel characteristics.

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