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Robot Mobility Systems for Planetary Surface Exploration – State-of-the-Art and Future Outlook: A Literature Survey

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1. Introduction

Mobile robots have been an essential element of space exploration to perform science on distant lunar and planetary objects. Past orbiter missions to Moon have shown evidence on the presence of ice inside the permanently shadowed polar areas. Similarly, Mars holds clues of life in the distant past. While data sent by orbiters provides a wealth of information and gives rise to new speculations and theories, in-situ science data from mobile rovers and landers is essential to validate or confirm them. “Mobility” is a vital element for a space missions due to valuable science return potential from different sites as opposed to static landers. Over the years, technology development has given rise to numerous mobile systems. Some of the systems are spin-offs from terrestrial applications like automobiles that use wheels, military tanks that use tracks and aerial balloons. Others have been developed purely for space application like hoppers and hybrid systems. Since 1970s, twelve surface missions have reported using mobile robots. Most of them used wheels as their mobility element for locomotion. Since surface space-exploration of planetary objects across the solar system has gained increasing importance in recent years, it is important to understand the state-of-the-art in mobile robotics and the technology development of the mobility system in particular. This need will be addressed in this chapter.

2. Aim of study

With advancement in research and technology, many mobile systems have been developed with different geometries, sizes, and configurations. These systems share different performance qualities under certain operational condition. There are limitations with every system in terms of certain mobility performance such as slope climb, obstacle traverse, speed, power consumption rate etc. Each system can be chosen depending on the type of mission, operation, expected science return, reliability and so on.
So far, many robotic vehicles have been designed and launched to different lunar and planetary bodies. They have been designed to operate remotely either through independent communication links or human-operated (Table 1). Over the years, technology advancements have been made that resulted in development of new mobility systems, due

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to ever-growing science requirements. Several such robot mobility systems have been reported in literature (Fig. 1). Here, we try to systematically classify all these systems depending on the type of mobility, as follows:

1. Aerial systems
2. Sliding systems
3. Rolling systems
4. Wheel-enabled systems
5. Leg-enabled systems
6. Track-enabled systems
7. Hoppers
8. Hybrid systems

Robot Name	Mission	Launch Year	Body	Country	Mobility
Lunokhod 1	Luna 17	10 Nov 1970	Moon	Soviet Union	Wheels
Prop-M	Mars 2	19 May 1971	Mars	Soviet Union	Skids
Prop-M	Mars 3	28 May 1971	Mars	Soviet Union	Skids
Lunar Roving Vehicle	Apollo 15	26 Jul 1971	Moon	USA	Wheels
Lunar Roving Vehicle	Apollo 16	16 Apr 1972	Moon	USA	Wheels
Lunar Roving Vehicle	Apollo 17	07 Dec 1972	Moon	USA	Wheels
Lunokhod 2	Luna 21	08 Jan 1973	Moon	Soviet Union	Wheels
-NA-	Phobos 2	12 Jul 1988	Phobos	Soviet Union	Hopper
Sojourner	Mars Pathfinder	04 Dec 1996	Mars	USA	Wheels
MINERVA	Hayabusa	09 May 2003	Asteroid Itokawa	Japan	Hopper
Spirit	MER-A	10 Jun 2003	Mars	USA	Wheels
Opportunity	MER-B	07 Jul 2003	Mars	USA	Wheels

Table 1. All reported space missions and mobile robots launched from the year 1970 to present

Aerial systems are particularly useful for "global" exploration cases. It can be useful in operations where there is presence of atmosphere. Other systems, that are listed above, while operated remotely in one, two, or few numbers would enable "local" exploration of the landing site. The maximum exploration range is limited to few tens of kilometres on the surface. But when deployed as a group or swarm, a "regional" exploration scale of a few square kilometers within reasonable mission duration is also possible. The geographic coverage can still be increased when deployed across different sites on the surface through a second auxiliary system (e.g. aerial).

In this Chapter, the result of a literature survey of mobility systems development in space agencies, research institutes and universities from the following space-faring nations - USA, Japan, Europe, Canada and Russia is presented. The Chapter aims to give an overview of already accomplished and currently ongoing research in mobile robot development

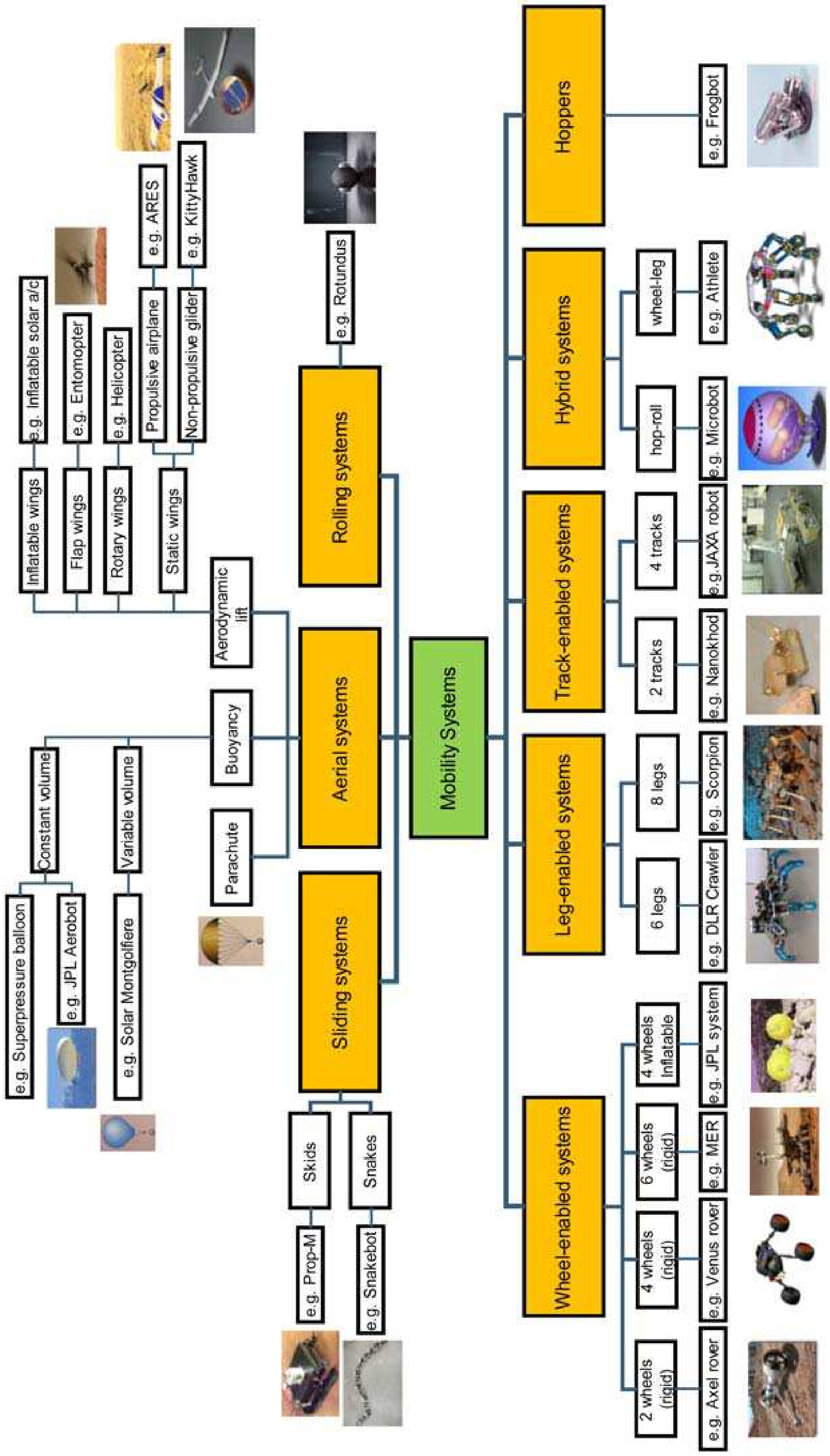

Fig. 1. Summary of past and present mobility systems technology development categorized based on mobility type

categorically and provide a brief description of the technical aspects of some of the mobility systems. In short, the study aims to answer the following questions:

1. What kind of robot mobility systems are developed or presently ongoing development for surface exploration?
2. What kind of mission-oriented applications would they fit in?
3. What are their pros and cons in terms of performance and reliability? What are their present readiness levels?

There are numerous ways to achieve mobility on an extra-terrestrial surface. This has been illustrated in Fig. 1. The chapter cannot provide a description of all the systems available, since such a scope is very exhaustive. Instead six systems are chosen based on their importance as well as literature coverage and then described subsequently with examples. The six systems chosen are wheel-enabled, leg-enabled, track-enabled, hoppers, wheel-leg hybrid and hop-roll hybrid systems. In the end, a comparative assessment of the six systems is also performed for different metrics qualitatively.

3. Wheel enabled systems

Wheels are commonly used for years to enable motion in terrestrial applications as in many on- and off-road vehicles. Wheel enabled systems or rovers can be categorized based on the number of wheels. Here two systems, eight and six-wheel rovers are discussed with examples.

3.1 Eight-wheel system

The well-demonstrated technology was first employed for space operations during the Lunokhod-1 and 2 missions in 1970 and 1973 respectively, to the lunar surface by former Soviet Union. Lunokhod-1 (Fig. 2) rover’s total mass was 750 kg and its “undercarriage” or suspension system alone weighed 105 kg (Kermurjian, 1990). The suspension consisted of eight active wheels that could enable the rover move longitudinally at speeds between 0.8 and 2 km/hr. The wheels were not designed to swivel and rover turning was enabled by varying the wheels’ rotational velocity at the left and right suspension. The suspension enabled Lunokhod-1 and 2 cover a distance of 10.54 and 37 km respectively on the surface during their operational lives.

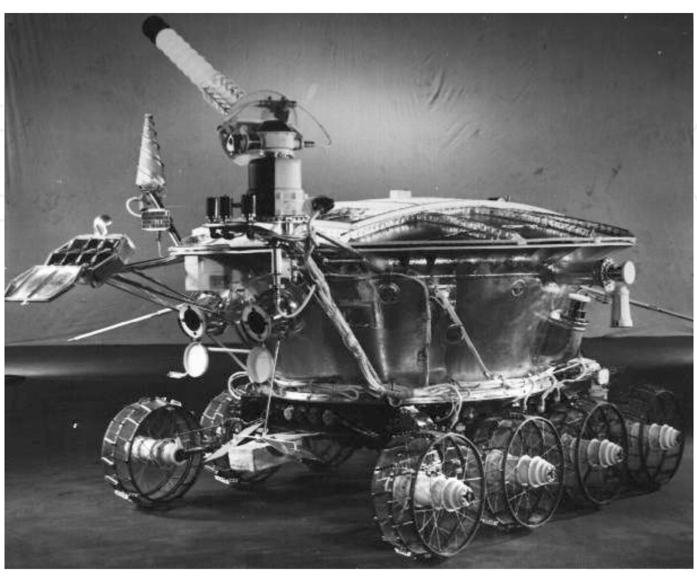

Fig. 2. Lunokhod 1 rover (Image Courtesy: Kermurjian, 1990)

The wheels of the rover were rigid with perforated, cleated rims. The rover also had a ninth free-rolling wheel that was used to monitor rover odometry and wheel slippage. Slip was estimated by comparing the number of revolutions of free-rolling and main drive wheels.

3.2 Six-wheel system

Eight-wheel enabled mobility systems as in Lunokhod are very heavy and are no longer being developed. In recent years, newer suspension concepts for rovers have emerged and are continuously being developed that promise high mobility performance without considerably impacting mass and power consumption constraints. The system typically consists of chassis, wheels, actuators, sensors, electronics, and steering mechanism. The notable one is the six wheel enabled rocker-bogie suspension system (Fig. 3) developed at NASA Jet Propulsion Laboratory and California Institute of Technology (Lindemann et al., 2005).

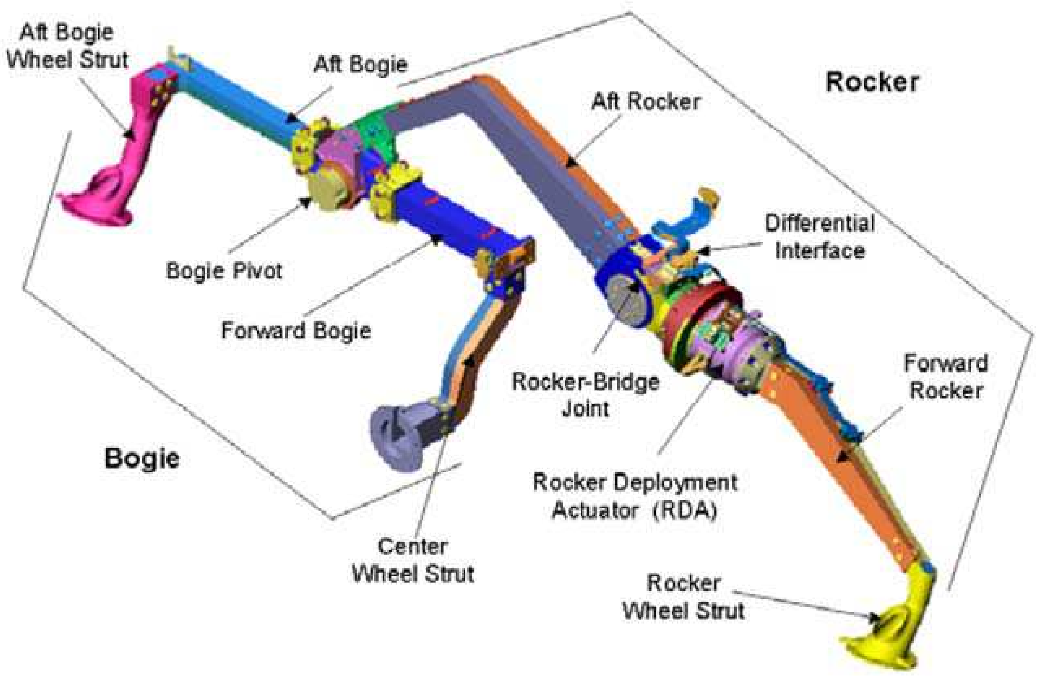

Fig. 3. Rocker-bogie suspension system (Image Courtesy: Lindemann et al., 2005)

The rocker-bogie suspension system uses a 6x6x4 wheel formula[1]. All the six wheels are independently actuated by DC motors and the front and rear wheels are steered by additional, identical DC motors. An internal differential mechanism in the rover's body connects the left and right rocker-bogie assemblies. The suspension system enables the vehicle to passively keep all wheels in contact with the ground even while traveling on severely uneven terrain. Typically, a vehicle with a rocker-bogie suspension system is capable of traversing obstacles with a height of at least the rover's wheel diameter. Tests have confirmed that the suspension system enables a rover to climb obstacles up to 1.5 times

[1] Wheel formula specifies the type of locomotion configuration associated with a rover. The formula is usually written in the form as follows:
Wheel formula = *Total no. of wheels* × *No. of actuated wheels* × *No. of steerable actuated wheels*

its diameter. The system also helps the rover in climbing loose-soil surfaces, during which the wheel's average pressure will be equilibrated. This is important for motion on soft terrain as excessive ground pressure results in wheel sinkage.

A limitation to the system as observed on Mars is excessive wheel slippage which results in total rover immobility. For example, Spirit and Opportunity rovers have remained trapped in loose soil for weeks. At the time of writing, Spirit was stuck in soft soil and unable to be recovered since. Such states also arise due to locomotion design constraints imposed by several parameters while designing the suspension system. One uncontrollable parameter is unknown local soil properties. Other constraints include lander's low stowage volume and lack of high-friction cleats on wheels due to possibility of entanglement with landing airbag during rover egress (Lindemann et al., 2006).

The rocker-bogie system is geometrically scaled to develop rovers of different mass class. Until now, JPL has used it in the Rocky7 testbed, Mars Pathfinder mission rover Sojourner, Mars Exploration Rovers (MER) Spirit (Fig. 4) and Opportunity. It is also being used to develop the 800 kg Curiosity (MSL) rover (Fig. 5) slated to be launched in 2016 (NASA/JPL/Caltech website, 2005).

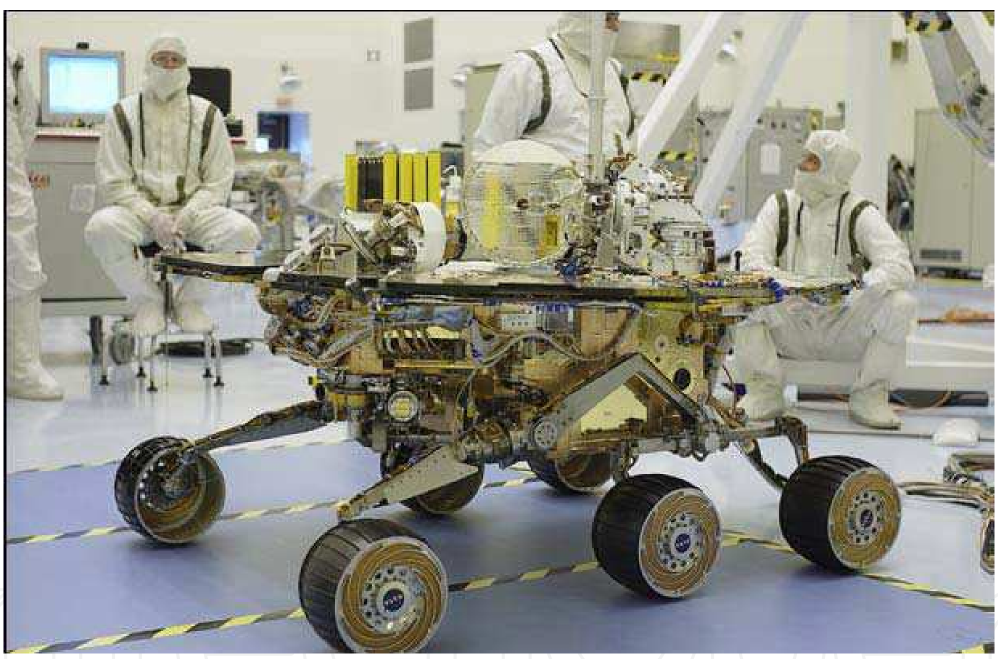

Fig. 4. Flight rover Spirit of Mars Exploration Rover missions (Image Courtesy: NASA/JPL/Caltech)

Enabling motion with wheels are not only limited to JPL rover applications. Studies from other space agencies such as ESA, JAXA also propose wheels (Roe et al., 2008; Kubota et al., 2005). This was evident during the early project phases of ExoMars and SELENE-II missions. However, unlike the rocker-bogie, these rovers differ in their system configuration. ExoMars employs longitudinal and traverse bogies (Roe et al., 2008). ExoMars is now planned to be launched in 2016. Presently, it is ongoing extensive modeling and simulation to analyse the terramechanics of the rover's mobility system at the authors' institute [Gibbesch et al., 2009]. SELENE-II uses the so-called Pentad Grade Assist Suspension or PEGASUS suspension system for their Micro5 testbed rover (Kubota et al., 2005).

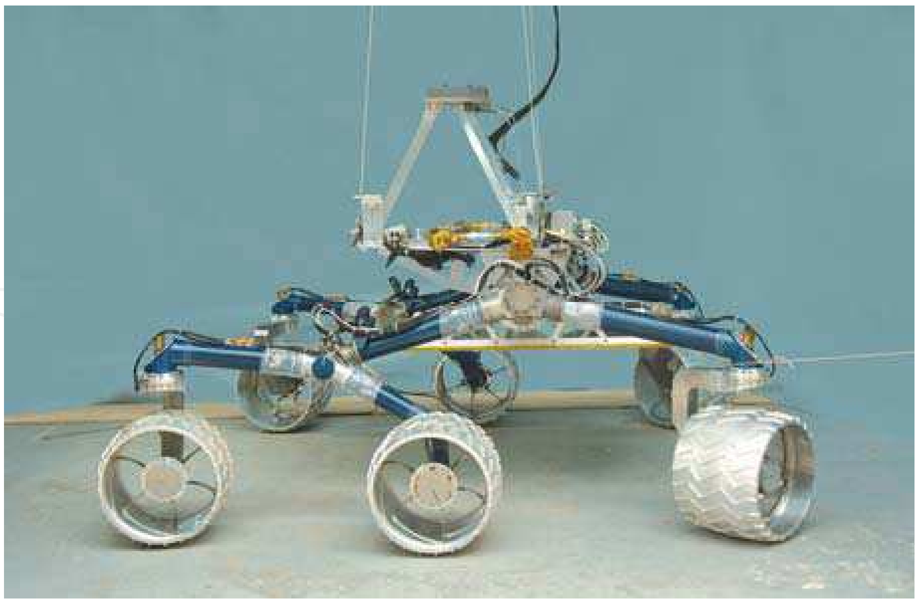

Fig. 5. Mobility model of Curiosity (MSL) rover (Image Courtesy: NASA/JPL/Caltech)

4. Track-enabled systems

Track enabled robots use crawl units or tracks that are commonly used for terrestrial mobile applications like military tanks and automobiles. These tracks are especially suited to motion on difficult terrain. Currently, track enabled systems are being considered for extra-terrestrial surface exploration also. Two types of such systems – Nanokhod and JAXA Track robot - are discussed below.

4.1 Twin-track system

The Nanokhod is a miniaturized track enabled robot (Fig. 6) that was developed based on Russian technology. Initially, it was foreseen to be launched with Beagle-1 Lander during ESA's 2003 Mars Express mission and was cancelled. The track system was then developed for BepiColombo mission to Mercury, which unfortunately was cancelled again. Since then, it is being immensely studied for lunar and other planetary missions (Klinker et al., 2005).

Fig. 6. Nanokhod dual-track system (Image Courtesy: Klinker, 2007)

The tracker consists of two "caterpillar" track units, a tether unit, and a payload cabin (Fig. 7). The caterpillar tracks are driven by four internal drive units. The drive units consist of a stepper motor attached to a 64:1 planetary gear in front of a clown and pinion stage. The output stage is a miniaturized harmonic drive whose input is coupled directly to the crown gear. The output is obtained through a flex spline and circular spline for track and arm drives respectively. The tracks are surrounded by protective walls.

Fig. 7. Nanokhod's miniaturized components (Image Courtesy: Klinker, 2007)

Nanokhod can move at a low speed of 5 m/hr (~0.14 cm/s). It is capable of climbing obstacles at least 10 cm high and trenched 10 cm wide sized (Klinker et al., 2007). The rover is small-sized. Electrical power is designed to be fed by a stationary platform (e.g. Lander) through tethers. Autonomous localization and vision-based navigation is performed based on model-based techniques that make use of Lander's fixed stereo camera images [Steinmetz et al., 2001].

4.2 Four-track system

The Advanced Space Technology research group in JAXA proposes a tracker for SELENE-II lunar mission (Wakabayashi et al., 2006). The mobility system for this tracker consists of four caterpillar crawl units with two on both sides (Fig. 8). Mesh structures are used in the crawl units. The units' links are meshed and equipped with L-shaped small lugs to increase traction. Metal mesh belts are used in each crawl unit.

Fig. 8. JAXA's four track system (Image Courtesy: Wakabayashi, 2006)

The nominal contact area of one unit is 100 cm^2. The crawl units (Fig. 9) take advantage of the compaction of regolith for mobility. The strategy of using mesh structures instead of track shoes enables reduction of cost, number of parts, and malfunctions.

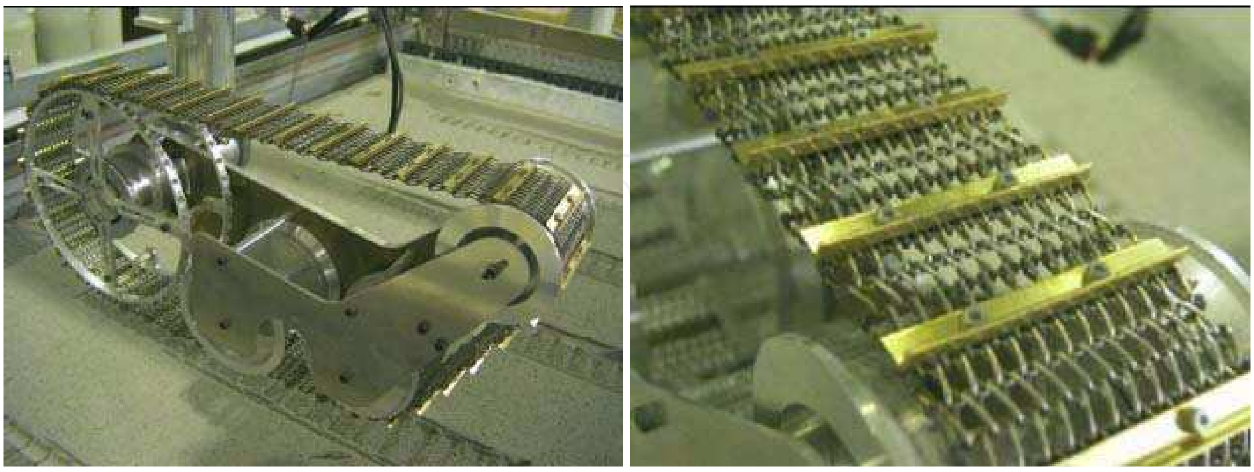

Fig. 9. Close look of a track (left); track mesh (right) (Image Courtesy: Wakabayashi, 2006)

5. Leg-enabled systems

Biological designs and neurobiological controls inspire robot development and have given rise to several robots. Biology offers working examples of robust and sustainable motion behavior. A few of the biology inspired designs that are leg enabled are discussed below.

5.1 Eight-leg system

SCORPION is an octapod (eight-legged), outdoor walking robot developed by German Research Center for Artificial Intelligence - Bremen, Defense Advanced Research Projects Agency and NASA (Fig. 10). It is designed to walk in dangerous, highly unstructured, rough terrain where mobility is crucial. The walker is 65 cm long and has a minimum height of 52 cm. In an M-shaped walking configuration, it is 40 cm wide. In a stretched-leg configuration, it is 35 cm high. The legs provide a ground clearance of 28 cm to the body. Each leg has three degrees of freedom (DOF). The legs consist of a thoracic joint for protraction and retraction, a basal joint for elevation and depression, and a distal joint for extension and flexion of the leg. The joints are actuated using 24 V, 6 W DC motors with high gear transmission ratio. The leg also features a spring element in the distal segment to reduce the mechanical stress (damping) and for measuring the ground contact force by an integrated linear potentiometer (Spenneberg & Kirchner, 2002).
The robot is powered by 3.0 Ah batteries. The robot is integrated with proprioceptive sensors namely motor encoders, Hall Effect motor current sensors (for each drive motor), and power management sensors. Motor encoders measure the relative joint angle whereas power management sensors measure current battery voltage and power drain.

5.2 Six-leg system

The DLR Walker is a Hexapod (six-legged) robot developed at the Institute of Robotics and Mechatronics of German Aerospace Center (Fig. 11). The legs of the robot are the fingers developed for DLR Hand-II (Görner, 2007; Borst et al., 2002). These legs/fingers consist of

Fig. 10. 8-legged system *SCORPION* (Image Courtesy: University of Bremen, DARPA, NASA)

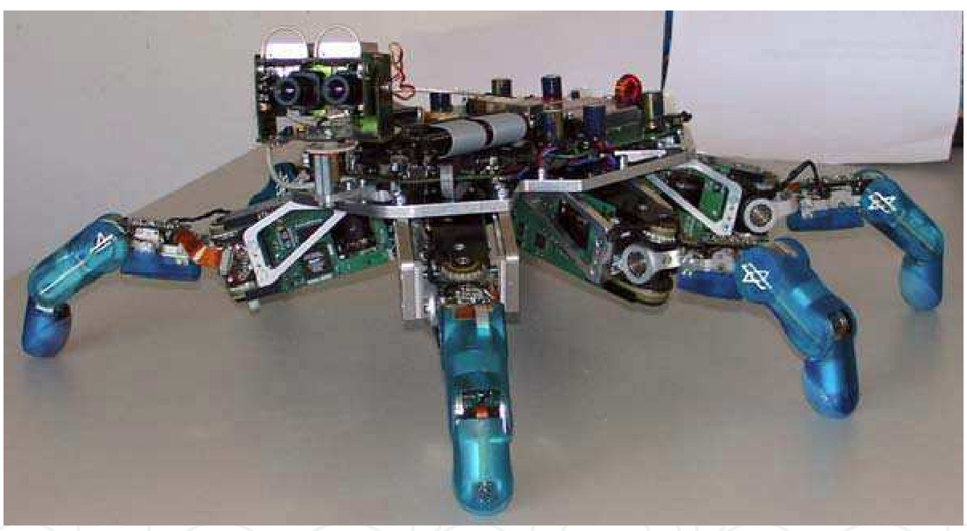

Fig. 11. DLR Walker robot (Image Courtesy: Görner, 2007)

three independent actuated joints that enable omni-directional walking. The base-joint actuating system, in each leg, essentially consists of brushless DC motors, tooth belts, harmonic drive gears and bevel gears. The base-joint is connected to the main body. It is of differential bevel gear type and movable in two DOF. The actuating system in the medial joint has relatively less power than the base joint and is designed to meet the conditions in the base joint when the leg is in stretched configuration. The third joint near the tip is passive and coupled to medial joint actuating system.

Each leg has three joint-position, three joint-torque, one forcetorque, three motor-torque, and six temperature sensors. The leg tip has a force-torque sensor that measures forces in six dimensions. Due to the force/torque sensing at the gear output it is most favorable to apply advanced so-called soft control algorithms. The most promising concept is to apply virtual

springs/damping forces to each joint in order to allow any kind of softly forced motion. Different walking gaits have been realized to overcome any complexly structured terrain.
Presently, this DLR walker is primarily used to study advanced navigation algorithms that autonomously map the 3D environment, localize itself and determine the next safe trajectory in this mapped environment. This is made possible by using the in-house developed Semi-Global Matching Method algorithm [Hirschmüller, 2008].

6. Hoppers

Hopping robots or hoppers were proposed as a cost-effective solution for planetary surface mobility to other systems. Unlike for other systems, where every small rock or hole on the surface is an obstacle to motion, hoppers are designed to hop over these obstacles. The importance given to design of these systems is simplicity and not high mobility performance. Hopping is performed at a certain velocity on a chosen trajectory without the need for accuracy of the destination. When used in swarms or groups of large numbers, these systems are capable of exploring a wide area.
An example of a hopping robot being designed is the Micro-hopper being developed by Canadian Space Agency (Dupuis et al., 2005). Hopping is enabled by a Shape Memory Alloy (SMA) actuator that utilizes heat from the Sun to store energy for the hop. SMA actuator elongates during the variation in day-night temperature. As a result, the current design reported in (Dupuis et al., 2006), allows one jump per day on Mars. A cylindrical structure with scissors is used to transfer energy for the hop. The hop is performed at a fixed angle of attack. The maximum horizontal distance covered in one hop is 3 m. The geometry of the whole robot is designed to be a regular tetrahedron as shown in Fig. 12. This allows landing in any direction and recovery after the hop.

Fig. 12. Illustration of CSA’s Micro-hopper (Image Courtesy: Dupuis et al., 2005)

7. Hybrid systems

The wheeled, tracked, and legged locomotion systems discussed earlier have their own advantages and disadvantages. For example, while wheels are capable of higher speeds than trackers and walkers on a flat terrain, it is relatively less capable of traversing obstacles as the other two. Hybrid robots consist of a combination of two mobility concepts that shares the advantages of both. Two kinds of such systems are discussed in the following sub-chapters.

7.1 Wheel-leg hybrid

Wheeled-leg bybrids have the advantage of higher mobility of walkers combined with the energy efficiency of rovers. The system as a whole can be designed to be highly modular, reusable, redundant, reconfigurable and with adequate margins. One such example is the DLR's hybrid concept that is proposed two have two mobility concepts in one: A six-wheeled rover system that carries a six-legged walking system [DLR Status Report, 2009].
The system can be favorably used to carry a small legged system on a flat terrain to a nonfriendly terrain where wheels cannot roll safely. In such circumstances, the legged system can be either carry the whole robot as shown in Fig. 13 (left) or dislodge from the top of the body and still carry the payload as in Fig. 13 (right). An example of the former scenario is using the main robot to the rim of a crater and then deploying the smaller robot to move down to the depths.

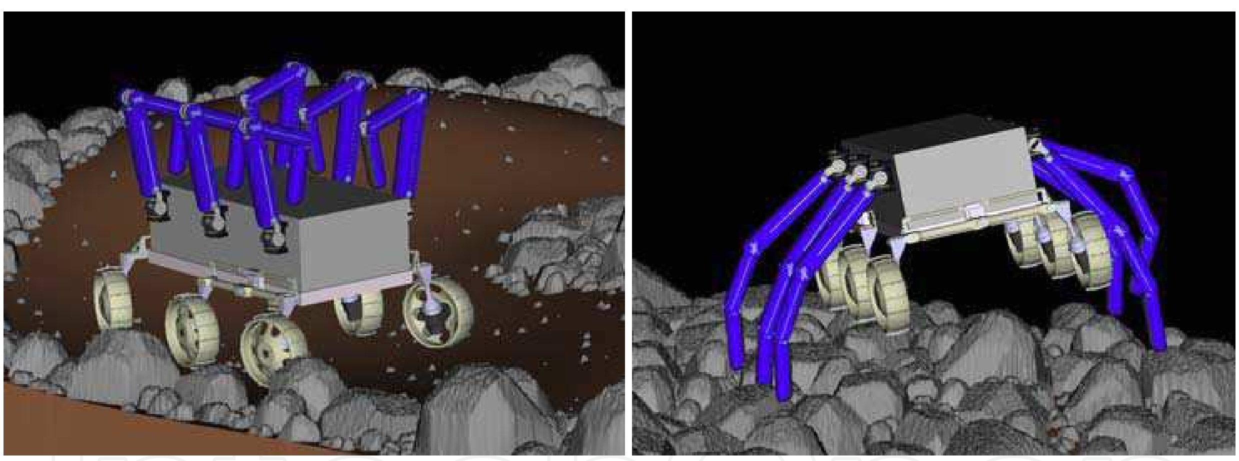

Fig. 13. Simulated DLR hybrid mobility concept in "wheel rolling" mode on flat terrain (left); "leg walking" mode on rugged terrain (right)

Wheels are used to roll over smooth terrain and legs for extreme terrain. The hybrid concept can also be used with unprecedented mobility capabilities. The concept is being realized in a hybrid lunar lander development called ATHLETE (Wilcox, 2007) by NASA (Fig. 14) primarily being developed to construct lunar outposts and assist astronauts (Morring, 2007).

7.2 Hop-roll hybrid

Hop-roll hybrid systems share the mobility concepts of both hopping and roll systems. The system can hop and the body has a ball-shaped design to aid rolling on inclined terrain. One such design called "Microbot" (Fig. 15) is proposed by Massachussetts Institute of Technology (Dubowsky et al., 2005). The system is designed to work with a swarm of other microbots to enable vast scale exploration and inter-communication possibilities between them (Fig. 16).

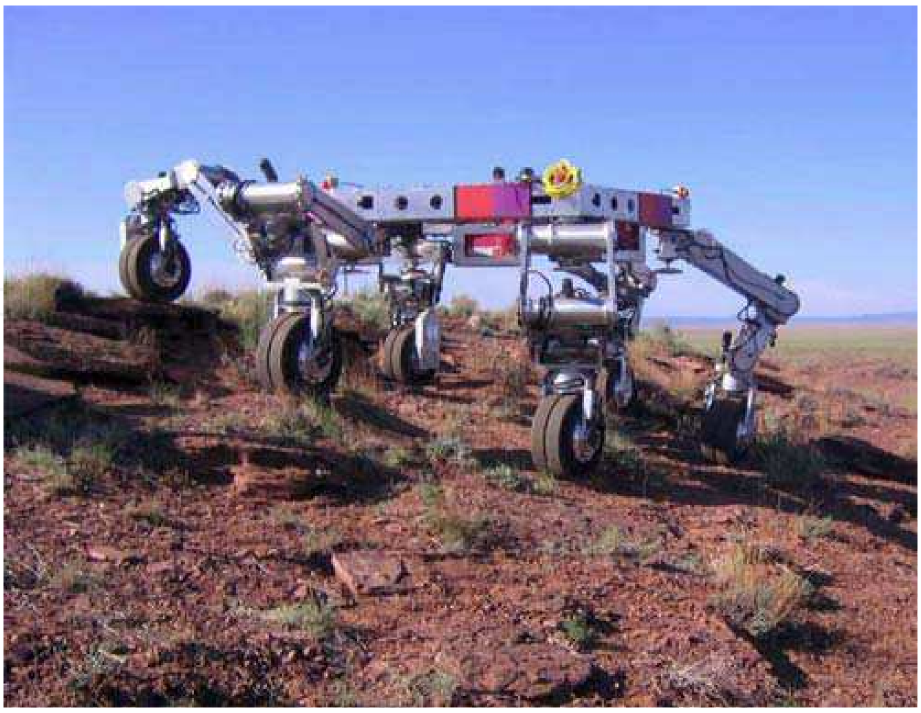

Fig. 14. Wheel-leg Hybrid system ATHLETE (Image Courtesy: NASA/JPL/Caltech)

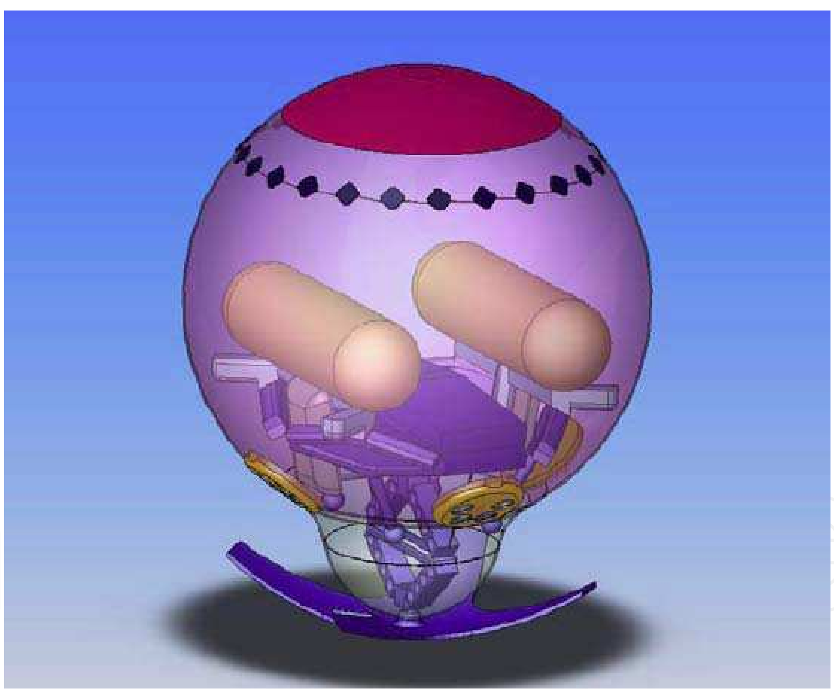

Fig. 15. Illustration of MIT proposed Microbot (Image Courtesy: Dubowsky et al., 2004)

Each microbot is proposed to be of low-mass (150 g), with a body diameter of 10 cm and has a horizontal distance hop of 1.5 m. The hop mobility is enabled by a bistable mechanism that is activated by dielectric elastomer actuators also called as Electro-active Polymer Muscle Actuators. Energy is transferred to the actuators over a few seconds or minutes, which are then continuously transferred by a short, high power stroke for a hop. Power is supplied by fuel cells. The design of the body, allows non-powered bouncing and rolling motion in slopes or in any inclined terrain.

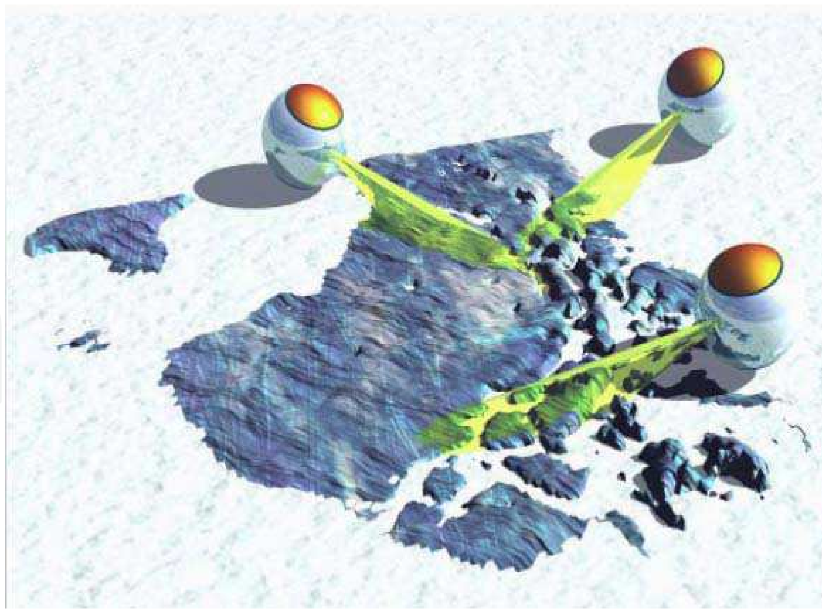

Fig. 16. Illustration of a swarm exploration scenario with microbots (Image Courtesy: Dubowsky et al., 2004)

8. Comparison of locomotion systems

A comparison of advantages and disadvantages of the different locomotion concepts will be treated hereafter. The comparison will focus on the aspects of mobility performance, reliability, energy consumption, obstacle negotiation and technical readiness levels. To compare locomotion systems comprehensively, experimental or simulation data based on operations in planetary terrain-like environment (planetary test-bed) is required. These experiments should be performed on similar test conditions. Such comparative data and subsequent comparative analysis of different locomotion concepts (wheel, leg, track enabled) are scarce in literature as it is influenced by many discrete parameters such as external dimensions, mass, number of wheels/legs, diameter of wheels etc. During this study, a step towards comparison of different locomotion concepts has been attempted qualitatively by inferring data from current state-of-the-art locomotion systems available in recent literature.

8.1 Metrics based comparison

The metrics are initially benchmarked with capabilities of a fictional locomotion system. These capabilities are then compared with the following 6 locomotion concepts discussed earlier – Wheel enabled system, track enabled system, leg enabled walker, hoppers, wheeled-leg hybrid, and hop-roll hybrid. The major strengths and weaknesses of each system were then marked qualitatively against different metrics. The selected metrics reflect the general performance of a robot's mobility based on state-of-the-art in present technology.

The metrics that are used and their description are as follows:

Maximum speed capability - Capability to move fast on a flat surface. This metric provides a relative measure to compare the distance reachable per day on a lunar or planetary surface.

Metrics	Assumptions
Maximum speed capability	Capability to move on flat terrain at a speed of 30 cm/s (on Earth)
Obstacle traverse capability	Step climbing ability equivalent to mobile element size (wheel diameter, length of legs).
Slope climb capability	Slope climb ability of 30° inclination
Soil sinkage	Medium sinkage of mobile element during motion on soil
Mechanical simplicity	Moderate level of mechanical complexity
Mobile element redundancy	Ability to perform and continue with motion after malfunction of two wheel assembly, assuming the vehicle having six components
Energy consumption rates	Capability to move with less battery power consumed per unit distance
Payload Mass Fraction capacity	In the range of 8 -12%
Soil interaction	Body contact with soil during motion process is moderate
Technology readiness level	Breadboard validated in space environment, i.e. TRL 5

Table 2. Benchmark vehicle assumptions

Obstacle traverse capability - Capability to move over obstacles/boulders relative to their mobile element size (wheels, legs etc.)
Slope climb capability - Ability to climb slopes covered with soft soil smoothly without excessive loads on one or more particular mobile elements (rear wheels, legs etc.)
Soil sinkage - Ability to move on soft soil over flat surface by having the least contact pressure without large slip, minimal sinkage and mobility resistance (depends on vehicle's mass)
Mechanical simplicity - Less complexity of the locomotion subsystem with regard to number of parts, linkages etc.; less moving parts
Mobile element redundancy - Capacity of the vehicle to continue on the mission objective in case of failure of primary mobile elements (wheels, tracks, or legs)
Energy efficiency - Ability to move with low power requirement/unit. In the case of walkers, the power consumed while raising and lowering of legs is added along with forward motion energy rates
Payload mass fraction capacity – Mass of payload to total robot mass ratio. Ability to carry significant science payload mass relative to total mass
Soil interaction - Ability to move by adequate ground clearance to corrosive planetary soil without unwanted interaction. This influences the capacity to withstanding hostile environment and long term effects (tolerance to corrosiveness).
Technology readiness level - Technology maturity and demonstration

8.2 Criteria

The criteria set for comparing the mobility systems are set in five different grade scales in Table 3. The assumptions of the benchmark vehicle (BMV) described in Table 2 are comparable with the third quality grade *** and given as BMV.

Metrics	*	**	***	****	*****
Maximum speed capability	lower than 50%	up to 50% low	BMV	up to 50% high	higher than 50%
Obstacle traverse capability	< 20 cm	up to 20 cm	BMV	up to 30 cm	> 30 cm
Slope climb capability	< 15°	up to 25°	BMV	up to 35°	>35°
Soil sinkage	Very high	High	BMV	Low	Very low
Mechanical simplicity	Very low	Low	BMV	High	Very high
Mobile element redundancy	No redundancy	Low	BMV	High	Very high
Energy consumption rates	Very high	High	BMV	Low	Very less
Payload mass fraction capacity	< 5%	5 – 8%	BMV	12 – 15%	> 15%
Soil interaction	Very high	High	BMV	Low	Very low
Technology readiness level	TRL 1 or 2	TRL 3 or 4	BMV	TRL 6 or 7	TRL 8 or 9

Table 3. Criteria for evaluating metrics

8.3 Result and discussion

Based on information reported in literature, the present state-of-the-art is understood and the metrics are graded accordingly. The result is given in Table 4.

Some advantages and disadvantages of the compared systems are summarized in Table 5 in general. In addition, the following points are worthy to note: A wheel enabled rover can roll at better speed on flat terrain and has moderate sinkage characteristics on soft terrain. A present-technology track enabled system has better slope climbing and obstacle traversing capabilities, but at the expense of high energy consumption. Generally, current systems for space missions are quite mechanically complex. Wheel enabled systems show considerable difficulties while climbing slopes over 15°, since the slip ratio drops suddenly. Track systems have better slope climbing and obstacle traversing capabilities than rovers.

Not many leg enabled systems developed for space applications are existent today, although a few vehicles are currently being developed in the US and Europe. These systems are highly stable while moving over obstacles, possess better mobility during downhill motion due to their Center of Mass position. However, it has the disadvantage of high power consumption, since power is needed for both lifting and forward motion of legs. Conversely, a wheeled rover is energy efficient.

Wheel enabled systems also possess good reliability and redundancy. Assume three six-wheel, six-track, and six-leg systems powered by motors individually at their mobility joints. Three malfunction wheels can still offer sufficient locomotion capacity in a wheel-enabled system as seen with MER. A track system has low reliability due to possibility of jamming of tracks and track units malfunction. Failure of one of the tracks may

Metrics	Wheel-enabled system	Track-enabled system	Leg-enabled system	Hoppers	Wheel-leg hybrid	Hop-roll hybrid
Maximum speed capability	***	***	***	*****	*****	*****
Obstacle traverse capability	***	****	*****	*****	*****	*****
Slope climb capability	**	***	***	*****	*****	*****
Soil sinkage	***	****	**	*****	***	*****
Mechanical simplicity	***	**	**	****	*	****
Mobile element redundancy	****	*	****	*	*****	*
Energy consumption rates	****	**	*	****	*	*****
Payload mass fraction capacity	***	***	**	****	*****	****
Soil interaction	***	**	****	**	***	*
Technology readiness level	*****	***	**	**	***	**

Table 4. Qualitative mobility systems comparison

lead to partial or total immobility. A leg enabled system can still move provided the failure no longer affects the motors and stow the malfunctioned legs over the body to avert contact with surface. The jamming of tracks in track systems can be averted by low-speed operation. Such compromises are less required for a wheel system. In any case, this argument validity depends on which motors powering the wheels, tracks and legs are malfunctioned. Failure of all three motor units on one particular side, will render any system go totally immobile.

Hoppers apply an easy, simple method of achieving mobility on low-gravity surfaces. However, the impact during every landing is a source of concern, since this may result in loss or damage to the entire system. Such is the case with hop-roll hybrids as well. An additional mobility advantage is that hop-roll systems can use their round body to bounce or roll easily in declined slopes without any power consumption.

The operational speed of a robotic vehicle is usually limited in the range of 10 cm/s due to safety concerns. It is limited by the type of gears used in the motor and power availability.

System	Advantages	Disadvantages
Wheels	• Better speed in even terrain • Simple and m ature technology • Adequate redundancy (mobility) • Payload weight-to- mechanism weight ratio high • Relatively low power consumption rates and energy efficient	• Relatively low slope climb capacity due to wheel slippage • Obstacle traverse capability relatively less compared to other concepts
Tracks	• Good terrain capability • Technology well understood in terrestrial applications • Better traction capability on loose soil • Handles large hinders, small holes, ditches better • Good payload capacity	• Inefficient due to friction of tracks • Low speed operation • Slip turning and friction • Low redundancy, jamming of parts and prone to failure
Legs	• Highly adapted to uneven terrain and hence better obstacle and slope traverse capability	• Mechanically complex • Control of walking is complex • Slow mobility • Impact after each step • Poor payload weight-to-mechanism weight ratio
Hoppers	• Better obstacle traverse capabilities • If power availability is flexible, can enable large scale exploration due to better speed	• Impact during landing after hopping had large risk of failure
Hybrids	• Shares the advantages of two locomotion concepts • Miniaturized hybrid hop-roll systems operating as swarm, enables exploration of larger area in a short time	• More complexity • Low technology maturity

Table 5. Advantages and disadvantages of mobility systems

The size of the vehicle is also a crucial factor while considering the mission scenario. It can be said that a mini-rover in the mass range of 30-100 kg is capable of accomplishing many science tasks by accommodating more integrated instruments and payloads. Also minirovers are capable of generating enough power for surviving the entire mission. Microrovers (5-30 kg) and nano-rovers (<5 kg) can be better suited for accomplishing specific mission objectives within limited range and power availability. These rovers are not capable of accomplishing a wide range of objectives like mini-rovers. However, in the case of nanorovers, there are various flexibilities possible in choosing a mission. Nano-rovers may not be independent in operation and deployed from Lander through tethers.

9. Conclusion

Trends in mobility technology are expected to have a major impact on surface exploration with robots in the future. Until the near future, the current trend of sending large payload mass using a single, large vehicle would be followed as can be seen in the case of Curiosity rover development that is bound for Mars. However, like in the case of earth-observation exploration, the increasing development of small satellites has made a major impact. A similar trend is expected in the surface robot development also. The current low to medium TRL of some mobility technology suggests that the present approach would change course to "lighter, cheaper and faster" missions. Some papers report exploration of Mars would follow a "paradigm shift", where swarm of micro robots would be launched with or without a mothership platform to deploy smaller ones in different locations across a planet. Also tethered exploration of dangerous slopes using parent-slave systems exploration strategy, where robots with conventional mobility like MER cannot access, is also expected. New missions would not only be designed to access multiple, easy locations but difficult and risky sites like deep mars "caves" where direct communication with an orbiter or lander is unfeasible. In such cases, the design of the robot's body as a whole to aid mobility as well as inter-robot communication would play a crucial role. The above mission scenarios are just a few cases, where currently proposed technologies provide a platform for exciting missions. In any case, it can be said that all missions would also follow a "high reliability, high science return and low cost" approach.

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