# Design of an Innovative Micro-rover with Multiple Modes for Mars Exploration

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## ABSTRACT

An Innovative Micro-Rover Platform with Tooling Arm (MRPTA) has been developed and tested in terrestrial-based analogue Mars and Lunar environments. The micro-rover can be used as a stand-alone system or in combination with a large rover to perform tasks to help human space exploration, such as scouting, sample scooping and return, and planetary science exploration, especially those tasks that explore the areas of rough terrains and steep slopes, which are dangerous to reach by astronauts and large rovers. The MRPTA consists of four major sub-systems: a platform with multiple modes, a tooling arm for sample scooping, an autonomous navigation device, and scientific instruments. All mobility requirements for the Micro-rover are realized by applying the basic mode of the platform that is the Linkage Mechanism Actuator patent technology. The key of this technology is that the robot mobility is performed by a flipper that is a simple 3-bar cam mechanism and used for controlling track configurations. The MRPTA was integrated and tested in terrestrial-based analogue Mars and Lunar environments. The testing results indicate that it has excellent the ability of climbing and navigating over uneven terrains, and can perform all required tasks adequately.

## 1 INTRODUCTION

The MRPTA project is part of the Exploration Surface Mobility (ESM) program of Canadian Space Agency (CSA). The objectives of the MRPTA project, in response to CSA-required MRPTA functionality and performance, are expressed by specific key challenging design features. The main objectives are: (i) to develop a robust reconfigurable mini-rover that possesses advanced mobility for access to hard-to-reach sites of interest for scientific explorations; (ii) to design the rover to have a weight of less than 30 kg in its baseline configuration; (iii) to provide the rover with the capability of navigating over significantly unstructured terrain through re-configurability of the traction system using modular components; (iv) to extend the mobility reach of the rover into normally inaccessible areas, by using a tether system that will allow traversing of slopes as steep as 65 degrees; (v) to allow the rover to navigate with limited human interaction, or even completely autonomous; and (vi) to allow the rover to perform adequately in a wide range and sub-optimal environmental conditions.

It is commonly accepted that mobile robots can be split into two categories: tracked or wheeled. Up to date, almost all planetary rover designs use wheels such as Rocker-Bogie [1], FIDO rover [2], and Rocky 7 [3], etc. However, a lightweight commercial rover that can traverse rocks or obstacles might be more preferably needed. In comparison to locomotion over flat ground, there are significantly more challenges in travelling over uneven terrains, such as climbing slopes, surmounting obstacles, and crossing rocks or ditches. Since it is expected that the rover must be able to lift its front pulleys/wheels forward and over the obstacles or rocks, and also to adjust the position of its center of gravity (COG) to protect it from turning over while ascending and descending, the terrain adaptability of the rover is much desired.

Under this circumstance, a novel micro-rover (MRPTA) composed of a platform, a tooling arm, a navigation device, and scientific instruments, was developed. The MRPTA's platform can be configured in four modes, i.e. 1) long track drive with flipper, 2) short track drive, 3) wheel drive with flipper, and 4) wheel drive modes. Meanwhile, the modes are interchangeable between each other.

## 2 MRPTA PLATFORM DESIGN

### 2.1 Mobility Requirements of the MRPTA

The planetary terrain is usually unpredictable, thus, the Micro-rover is desired to have: (i) the adaptive terrain ability to navigate steepness slopes such as 65$^{o}$ with tether aided and 30$^{o}$ without any aid, moist soil and mud, sand and small rocks, etc; (ii) the maneuverability on a 15$^{o}$ slope; (iii) the capacity to withstand a free fall from a height; and (iv) the capability of the recovery from tumbles when the robot lands on its "back".

### 2.2 Basic Mode of the MRPTA [4 ~ 6]

The basic mode of the MRPTA is a long track drive with flipper that is a patented linkage mechanism actuator technology (LMA). It is used to realize all mobility requirements for the MRPTA through its track configuration controlling mechanism, i.e. the flipper. The rotation of the flippers allows the rover chassis to tilt up and down, and provides tremendous ability for surmounting obstacles.

It is well known that terrain adaptability of a tracked mobile robot depends on the configurations of the tracks. In order to actively adapt the terrain variations, the track configuration should be readily changeable to match the variation. Meanwhile, the robot must have the ability of lifting its front pulleys forward and upward the stairs or obstacles, and can adjust the position of its COG to protect it from turning over while ascending and descending. The creation of the flipper is based on these requirements. The mechanism is a 3-bar cam mechanism consisting of two moving elements, i.e. crank and follower, and a cam fixedly mounted on the mobile robot's chassis.

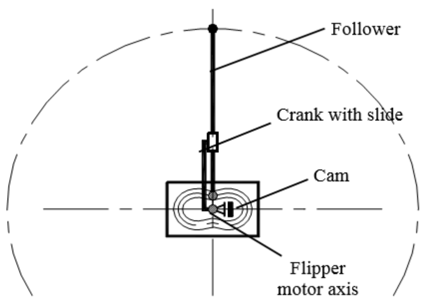
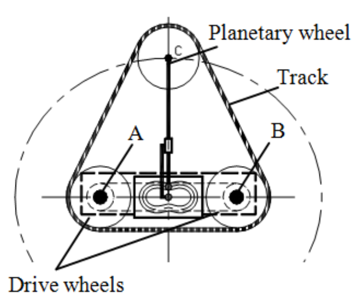
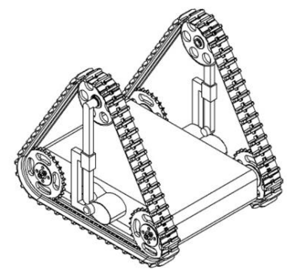



*Figure 1: Schematic diagram of the track configuration-controlling mechanism, i.e. the flipper*

The track's variable configurations are provided by simultaneously controlling the position of planetary wheel which is mounted on the end of the follower. The planetary wheel's location is controlled precisely by the flipper. In general, the platform of this robot includes a chassis having a pair of drive/driven pulleys at each side, a pair of flippers where planetary wheels are mounted, and two tracks as shown in Figure 2.




(a) Schematic diagram



(b) Kinematic model

*Figure 2: Schematic diagram and kinematic model of the LMA*

It is known that the trajectory orbit of the center of the planetary wheel is a closed curve that is determined by track length, wheelbase, and diameter of the drive/driven pulleys. The curve will be ellipse having focal points at two drive/driven pulleys' centers when the diameter of planetary wheel is equal to that of two pulleys. Meanwhile, the trajectory is also constrained by the cam's profile.

Referring to Figures 1 and 2, the motion path of the center C of the planetary wheel must be an ellipse with focal points at two drive wheels' center A and B when the diameters of all above wheels are equal. The motion path $\overline{M_0M_{18}}$ of the other ending point M of the follower is obtained as shown in Figure 3, when the follower turns clockwise and makes point C to move along the elliptical trajectory $\overline{C_0C_{18}}$. The path $\overline{MC}$ line of the follower always goes through the crank revolution center O. Likewise, provided that the motion path of point M is controlled based on $\overline{M_0M_{18}}$ trajectory and $\overline{MC}$ line through the revolution center O is a must, the point C can only move along the ellipse.

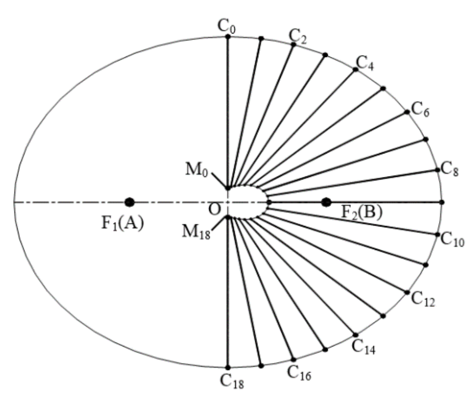



*Figure 3: Motion trajectory of the planetary wheel center C*

Based on the above principle, the track configuration-controlling mechanism, i.e. the mechanism of controlling the position of the planetary wheel was designed as shown in Fig. 1. The mechanism includes a follower, a crank driven by a motor and a cam which is fixedly mounted on the platform. The "$\infty$" profile of the cam is exactly the same as the motion path $\overline{M_0M_{18}}$, so that the path of the planetary wheel center $C$ precisely fits the elliptical trajectory $\overline{C_0C_{18}}$.

Specifically, in order to prevent tracks from coming off wheels, it is necessary to keep the loop of the track continuously tensioned. For this purpose, the track configuration-controlling mechanism is slightly modified by adding a spring, and dividing the follower into a tension follower and a guider as shown in Figure 4.

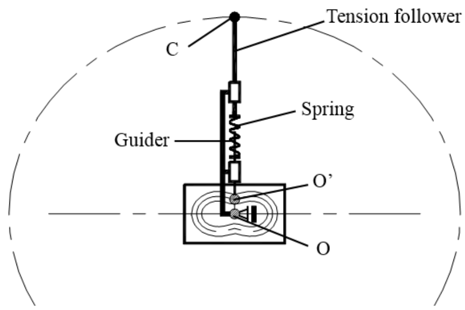



*Figure 4: Schematic diagram of the track configuration-controlling mechanism with tension springs*

The tension follower and guider can rotate not only around axis O', but also move linearly along the direction of $\overline{OO'}$. Therefore, the tension follower and guider have the same rotating speed and orientation. During the motion of the planetary wheel, an elliptical trajectory is achieved due to the constraint of the cam's profile. As well, the distance between points C and O' is constant. The spring provides a constant force to tension the tracks. Accordingly, the track configuration-controlling mechanism has a dual function, namely, controlling the configurations of the tracks and automatic tensioning of the same tracks.

Variable configurations of the robot can be obtained by rotating the track configuration-controlling mechanism. Figure 5 shows a few examples of different configurations that this robot can realize.

These configurations are particularly useful in regard to surmounting obstacles or rocks, ascending/descending slopes, and crossing ditches. As well, they are useful in increasing the height of sensors on the platform and recovering from tumbles when the robot lands on its "back".

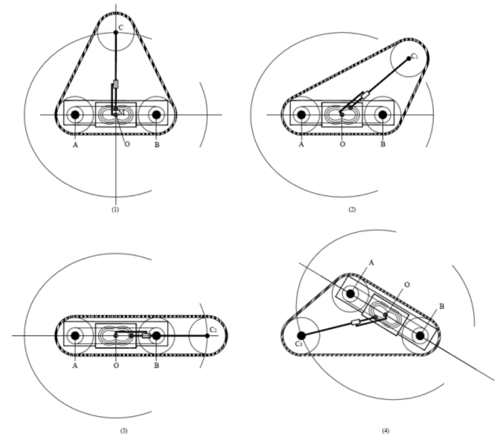


*Figure 5: Variable configurations of the robot*

The obstacle surmounting process of the rover is described in Figure 6, (a) the flipper is rotated until the center of the planetary wheel is higher than the obstacle height; (b) the rover moves forward and upward until its front pulleys climb over the obstacle; (c & d) the flipper rotates to the rover's back and starts to surmount; (e & f) the flipper continuously rotates until the rover can land without impact.

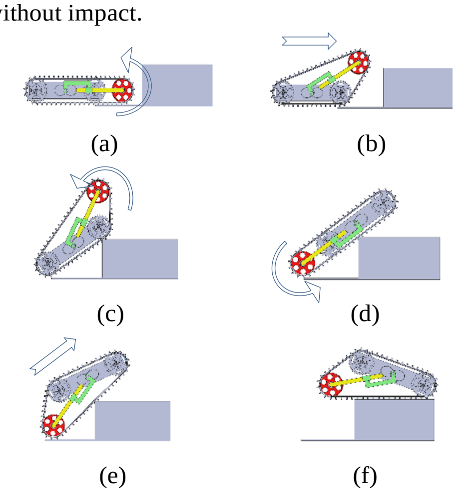


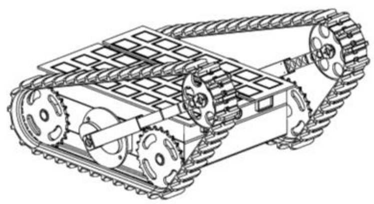

*Figure 6: Rover surmounting an obstacle*

The basic mode of the Micro-rover developed by ESI can change configurations with the help of a set of modular elements that can be easily attached and detached. The variety of configurations is provided to suit various terrain and operational conditions. The platform can operate as tracked or wheeled configurations with or without flippers. This design is rugged but exceptionally lightweight, with a mass of less than 30 kilograms, making it ideal for planetary exploration.

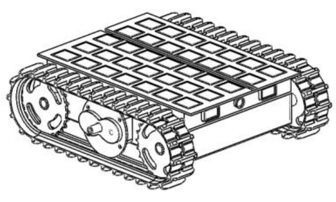
### 2.3 Derivatives of MRPTA's Basic Mode

All mobility requirements for the Micro-rover can be realized by applying the basic mode, i.e. long tracks with one pair of flippers. The rotation of the flippers allows the rover chassis to tilt up and down, and provides tremendous ability for surmounting obstacles.

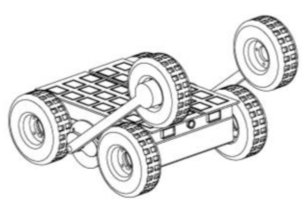
Even though the basic mode can meet almost all uneven terrains, some new derivative modes are considered for some special requests such as big clearance, special orientation of platform, and irregular rocks, etc. Therefore, the mobility should be further enhanced by applying multiple derivative modes as shown in Figure 7.



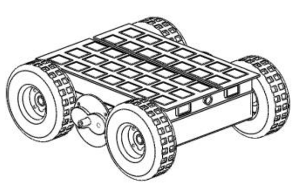
(a) Long track drive with flipper



(b) Short track drive



(c) Wheel drive with flipper



(d) Wheel drive

*Figure 7: Multiple drive modes of the MRPTA*

## 3 TOOLING ARM DESIGN

Tooling arm is a major component of the MRPTA. It was designed for the sample acquisition and mounted in the front of the MRPTA's platform. In order to get a light and compact tooling arm, a new scooping mechanism was presented, which consists of a lead screw, a nut, and a four-bar linkage mechanism. The scooping mechanism uses one motor to realize two motions, i.e. a linear motion for the lead screw and a scooping rotation (i.e. either opening or closing state of a scoop).

As shown in Figure 8, the scooping mechanism is a combined mechanism of a screw mechanism and a four-bar linkage mechanism. The screw mechanism is composed of a lead screw **4** and a nut **5**. The four-bar mechanism includes a slider (lead screw **4**), a coupler link (link **12**), a side link (scoop **6**), and a frame (shuttle **13**). The lead screw **4** plays two roles, i.e. it serves as both a screw in the screw mechanism and a slider in a four-bar mechanism. In this combined mechanism, the nut **5** is a driver member that is not only attached to the lead screw **4**, but also drives the lead screw **4** to move linearly in a vertical direction.

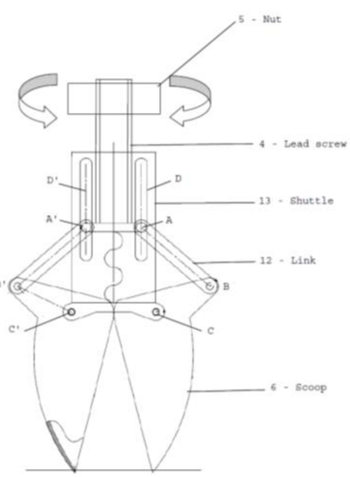
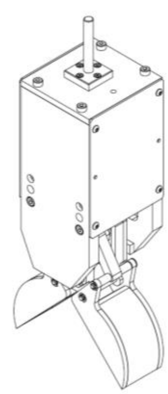
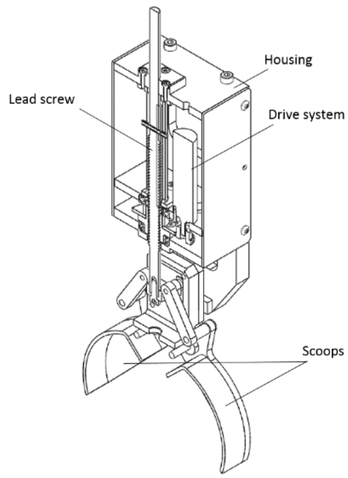



*Figure 8: Scooping mechanism schematic*

The tooling arm assembly in Figure 9 includes a drive system which is an assembly of a motor and a gearhead, a scooping mechanism, and a housing.



(a)




(b)

*Figure 9: Tooling arm structure*

## 4 DESIGN OF THE AUTONAMOUS NAVIGATION SYSTEM [9]

The autonomous navigation system of the MRPTA is capable of moving the rover to predefined position(s)/orientation(s) while continuously mapping terrain, assessing its traversability and choosing most appropriate path to follow. The tasks of autonomous navigation includes rover pose estimation, environment assessment, and rover motion execution.

The system consists of several interconnected components: Pose Estimator (PE), Terrain Evaluator (TE), Map Manager (MP), and Path Planner (PP). The PE uses a minimal sensor configuration consisting of an azimuth gyroscope, inclinometer and wheel odometry. The PE provides reliable pose estimates in spite of pronounced slippage by employing extensive use of fused data. The TE uses a nodding laser scanner which continuously sweeps the area in front of the platform and constructs a "traversability grid" (TG) of the surrounding area. Multiple TGs are constantly constructed along the platform motion path are combined into a terrain map maintained by the MP. The PP uses this map to compute a motion path. Thus, the obtained path is executed by the motion controller and remains current until it is contradicted by the most recent map – at which point it is re-planned.

## 5 SCIENTIFIC INSTRUMENTS

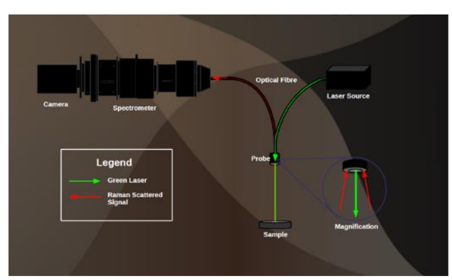
The rover is expected to perform a preliminary analysis of the sample area prior to sample collection. There are two parallel investigations as to the appropriate pre-sample analysis. The first method under consideration is an X-ray induced fluorescence instrument. This is commercially available technology. The approach is to purchase an instrument and then fully integrate it with the MRPTA robot. The second pre-sample analysis methodology is to use laser induced fluorescence to identify interesting samples prior to collection. Both of these methods target specific fluorescing minerals or organic compounds. These two types of instruments as demonstrated below were separately tried for use with the MRPTA.

Niton XL3t 950 GOLDD+ XRF [7] in Figure 10 is a non-destructive analytical technique used to identify and determine the concentration of elements present in solid, powdered and liquid samples. The XRF spectrometer measures the individual component wavelengths of the fluorescent emission produced by a sample when irradiated with X-rays.

*Figure 10: Niton XL3t GOLDD+ XRF analyzer*

The other instrument that has been also tried is a high performance, 2D detector Raman spectrometer [8] with a reduced footprint shown in Figure 11. This instrument includes 4 major components: a 550 to 1000 nm spectral range (within 5% of the limits) Raman / Broadband Spectrometer, a high resolution Area Scan monochrome camera (12 bit readout), a 40-50 mWatt tunable (1.5nm) laser with line at 532nm (Raman and FLUORESCENCE capable), and a fiber probe. The probe has to be fixed in the front of the chassis near the tooling arm while the other three components can be mounted anywhere on MRPTA.

(a)



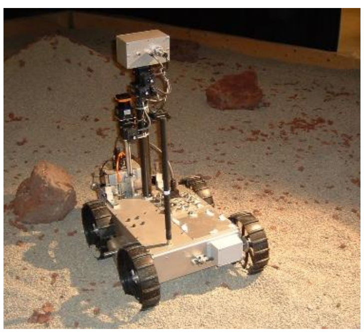

(b)

*Figure 11: Multi-channel, portable UV-Spectrometer*

## 6 SYSTEM TESTING

The MRPTA with multiple modes as shown in Figure 12 has been built and tested based on compliances requirements including mobility, tele-operation, autonomous navigation, and scientific experiment tests, etc.

(a)



(b)

*Figure 12: MRPTA with selected traction modes*

Mobility test results indicated that MRPTA had a stronger climbing and navigating abilities. For example, it can climb 35º slope without any aid and 65º slope with tether aided; also it has the ability to surmount the obstacle with 30cm height.

The results of the tele-operation tests showed that MRPTA complied with the requirements such as traveling and communication range of 500 meter, the mobility verification of the different modes, the scientific survey and sample acquisition, and LIDAR map updating, etc.

The tests for autonomous execution of "scooping", i.e. taking samples of the soil using tooling arm was also performed. It was observed that MRPTA could gradually open the scoop, reach the ground and collect the soil. For scouting type missions, the accuracy of MRPTA observed at the return to starting point was approx. 2% of the distance travelled for the missions of approx. 100 meters, executed at average speed of 0.1m/sec. The obtained accuracy is better than the reported by most of the systems relying on dead-reckoning and inertial sensors [9].

## 7 CONCLUSIONS

An Innovative Micro-Rover Platform with Tooling Arm (MRPTA) was introduced. Its platform has multiple modes that make MRPTA suitable for various different terrains. Especially, (i) ascending and descending slopes or surmounting obstacles and rocks forward or backward can be realized by changing the position of the planet wheel of the flipper; (ii) moving stability is ensured by controlling the position of the planet wheel to adjust the location of COG; and (iii) the platform orientation can be controlled by using the flipper.


## Acknowledgement

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