Rev. Cubana Fis. **36**, 46 (2019) ARTÍCULOS ORIGINALES

# MEASURING THE PERFORMANCE OF A ROVER WHEEL IN MARTIAN GRAVITY

## MIDIENDO EL COMPORTAMIENTO DE UNA RUEDA DE ROVER A LA GRAVEDAD DE MARTE

J. Amigó-Vega[a†], G. Viera-López[a], A. Serrano-Muñoz[a] and E. Altshuler[a]

Group of Complex Systems and Statistical Physics, University of Havana, 10400 La Habana, Cuba; joaquin.amigov@gmail.com[†]
† corresponding author

Recibido 10/3/2019; Aceptado 10/5/2019

With the increase of planetary exploration missions and thereby the resultant increase of extraterrestrial rovers deployed, their mobility performance meets new challenges. Wheel-soil interaction plays an important role in the movement of these rovers. Our research addresses the study of this interactions in the first moments of the trajectory. The investigations reported so far, focus on long-distance motion (approx. 20-30 cm). However, the authors believe that the firsts interactions are crucial for the future performance of the motion. Here, by means of a device that allows multiple and precise repetitions of a wheel rolling experiment at controlled gravities, we characterize the movement of a wheel on sandy soil, in the gravity of Mars. Our study reveals that gravity influences the performance of the wheel, under these conditions. The experiments show that, as the gravity decreases, the rolling efficiency also decreases.

Con el incremento de las misiones de exploración espacial y por tanto el incremento resultante en la cantidad de rovers desplegados, su eficiencia de desplazamiento se enfrenta a nuevos retos. La interacción rueda-suelo juega un papel importante en el movimiento de estos rovers. Nuestra investigación está dirigida al estudio de esta interacción en los primeros instantes de la trayectoria. Los trabajos reportados hasta la actualidad, se enfocan en desplazamientos de largas distancias (aprox. 20-30 cm). Sin embargo, los autores creen que los primeros instantes son cruciales en el futuro desempeño del movimiento. En este trabajo, usando un dispositivo que permite múltiples y precisas repeticiones de un experimento de rodadura a gravedades controladas, se realiza una caracterización del movimiento de la rueda sobre suelo arenoso a la gravedad de Marte. Nuestro estudio revela que la gravedad influye en la eficiencia de rodadura. En los experimentos realizados a medida que disminuye la gravedad, la eficiencia del movimiento de la rueda empeora.

PACS: Image analysis (análisis de imágenes), 87.57.N-; Movement and locomotion (movimiento y locomoción), 87.85.gj; Motion sensors (sensores de movimiento), 07.07.Df; Mars (Marte), 96.30.Gc

## I. INTRODUCTION

Walking or rolling on a sandy soil involves a delicate balance between mechanically stable and flowing states: an excess of the latter can easily prevent any further motion of a wheeled vehicle. That is perhaps what happened with the Mars *rover Spirit* as it sank into and tried to escape from a shallow sand dune in 2009, after 5 years of fulfilling an extremely successful mission [1]. At the In Situ Instrument Laboratory at NASA's Jet Propulsion Laboratory (Pasadena, California), scientists maneuvered with a clone of Spirit in a sandbox designed to imitate the soil conditions in the Martian environment. While the compositional and grain size distribution of the Martian soil were accurately imitated on Earth, other peculiarities associated to the reduced Martian gravity were impossible to reproduce. The team used a lighter version of the clone to imitate smaller weight in Mars but the method could not account for the possible changes in the behavior of the soil itself due to smaller-than-Earth gravity, which could be an important factor on this interaction.

Due to the enormous practical importance of the performance of wheels in granular soils there is a relatively large amount of literature on the subject, which concentrates on parameters of direct engineering impact such as the nature of the soil, the weight, size and surface design of the wheel, and the imposed velocity or torque [2–9]. The performance of granular materials in such conditions is key for space exploration and eventual colonization of space bodies such as the Moon and Mars: in those cases, our relatively poor understanding of the statics and dynamics of sand [10–14] is aggravated by lower values of $g$, which substantially complicates experimental efforts [15]. Reproduction of lower than Earth gravities requires complex experimental facilities [16–21], which has hindered the research efforts in the subject.

However, pioneering experiments to examine the performance of wheels at low gravities in a controlled environment have been performed recently. The first was reported by Kobayashi *et al.* in 2010 [22]: based on parabolic flight maneuvers, they studied the performance of a cylindrical wheel in "variable gravity conditions", where plateaus at gravities near that of Mars were achieved. The typical experiment lasted from 15 to 30 seconds, depending of the gravity, at a constant 0.314 rad/s velocity. The authors drive two main conclusions. Firstly, that the wheel's sinkage is independent from gravity, a result later explained in 2014 by Altshuler *et al.* through low gravity experiments on an spherical intruder [23]. Secondly, that the increase of soil "flowability" at small gravities lessens the shear resistance of the wheel rotation, so it is unable to hold sufficient traction, and slips more, as compared to ground experiments.

Curiously enough, the same group has suggested that conducting Earth experiments on wheels with the same mass of those intended to roll on a lower gravity environment, allows the prediction of performance in the extraterrestrial environment [24, 25]. Other low-gravity experiment was reported as recently as 2017 by Viera-López *et al.* [26]: they set up a large Atwood machine capable of achieving very stable and repeatable Martian gravities, while a miniature reproduction of NASA's Mars rover wheel rolls on sand into an accelerated laboratory. Preliminary results indicated a larger slip ratio of the wheel at Martian gravity, in agreement with Kobayashi *et al.* [22].

In this paper, we benefit from the precision and experimental reproducibility of the setup reported in [26] to study systematically the performance of a realistic scaled-down model of NASA's Mars rover wheel under different experimental parameters, at the gravity of Mars ($g_{\text{Mars}} \approx 0.4\, g_{\text{Earth}}$) and the gravity of Earth.

## II. EXPERIMENTAL WORK

In Fig. 1, one of the main components of the experimental setup reported by Viera-López *et al.* [26] is shown, which has been used in the present report.

Figure 1. Lab-in-a-bucket: photograph of the accelerated laboratory. When attached to a 15-m long Atwood machine, the wheel can "feel" an effective gravity equivalent to that on the surface of Mars.

The most important measured variables are the actual linear displacement and the angular displacement. The efficiency and slippage are inferred from other measurements. Below we describe how we quantify these parameters.

The wheel is attached to a DC motor with a 270.9 steps-per-revolution pulse encoder used to measure the rotation of the wheel while rolling on sand inside the instrument. This measured angular velocity is used to calculate the linear displacement along the perimeter of the circular trajectory following the formula

$$x_{\text{calculated}}(t) = \int_0^t r\omega(t)\, dt, \tag{1}$$

where $r$ is the radius of the wheel. The function $\omega(t)$ can be obtained by a numerical integration of the encoder pulses in time. This calculated linear displacement assumes no slippage and can be used as a reference to estimate the efficiency if we were able to measure the actual linear displacement.

We can also directly obtain the actual linear displacement of the wheel, based on the motion of its center of mass, by processing the images taken with the camera on top of the instrument. Consider the initial position of the wheel, described as a vector in polar coordinates, where $R_0$ is the initial distance between the center of the wheel and the central pivot placed in the instrument, and the angle $\alpha_0$ is the initial angle referred to the positive x axis, in the coordinate system placed in the central pivot.

The wheel describes a circumferential trajectory due to the holonomic restriction imposed by the central pivot. To obtain the displacement up to a certain time, we can use the following expression

$$x_{\text{measured}}(t) = R_0[\alpha(t) - \alpha_0], \tag{2}$$

where $\alpha(t)$ and $\alpha_0$ are the angles defined in Fig. 2.

Using the calculated and measured values of linear displacement, we are able to quantify the instantaneous slippage of the wheel for a given value of gravity, angular velocity, mass and granular matter properties.

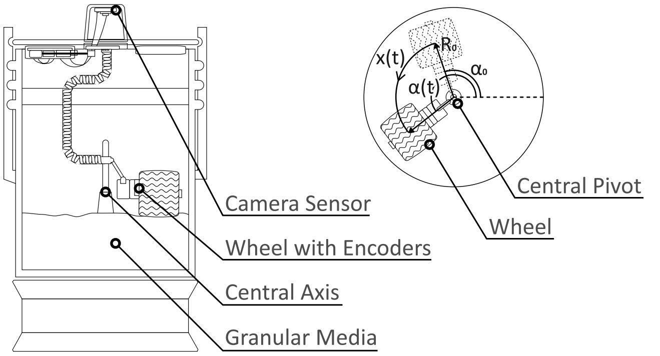

Figure 2. Motion of the rover wheel into the accelerated lab. The wheel moves on the sand describing a circumference around the vertical symmetry axis of the instrument. The inset shows some basic parameters characterizing the motion.

The data of $g_{\text{eff}}$ was obtained directly through an inertial accelerometer.

The instantaneous efficiency is calculated as the ratio between the time derivatives of *x calculated* and *x measured*, using the following formula

$$\text{efficiency} = \frac{\dot{x}_{\text{measured}}}{\dot{x}_{\text{calculated}}}. \tag{3}$$

We designed a set of experiments in order to understand how the differences of gravity between Earth and Mars could affect the wheel's performance while it is rolling on sandy soil. First, we performed experiments on Earth and Mars gravities and evaluated the total slippage after the same amount of time in both conditions. Next, in order to quantify the role of the weight's difference, we increased the mass of the wheel before performing the Mars gravity experiments, in a factor that compensates the gravity decrease. With this "normalized mass" we were able to quantify the slippage with the same weight at both gravities.

We used, for this experiments, a scaled-down 3D printed wheel similar to the ones used by the Mars *rover Curiosity* [27]. The radius and width of the 'replica' were reduced relative to the original rover wheel. In order to reproduce as good as possible the behavior of the wheel on Mars conditions and validate the results, considering the size differences, a mass scaling was made.

The wheel was scaled assuming that the density is conserved, and that all other dimensions scale as the size of the wheel. Assuming that $m$, $r$ and $w$ are the mass, radius and width of the 'replica' and $M$, $R$ and $W$ are their analogues for the original wheel, it is possible to estimate the mass of the 'replica' according to

$$\frac{M}{R^2W} = \frac{m}{r^2w}. \tag{4}$$

Substituting M = 900/6 kg/wheel, R = 0.25 m and W = 0.4 m from a realistic Mars rover [27] and r = 0.07 m, w = 0.049 m for our replica, we get a normalized mass of 1.44 kg.

To measure the mass of the wheel, we attached the wheel to the DC motor and placed it inside the instrument on its final position. In the bottom of the instrument, instead of the granular media, we placed a small high-resolution weighing scale. We called the value obtained "effective mass", because this is the mass of the wheel+motor system that is in direct contact with the granular media. This "effective mass" value (1.05 kg) is the one used for calculations on the next section.

## III. RESULTS

In the first experiment, the wheel was configured to roll over sand at Mars gravity. The angular velocity used was of 4 rad/s and the mass of the wheels was 1.05 kg, which is of the order of magnitude of the mass calculated with the scaling (we did not use the calculated value of 1.44 kg due to technical reasons). The actuator, a motor attached to the wheel, was configured to receive the start signal when detecting the system's stabilization at the effective gravity ($g_{\text{eff}}$).

The second experimental configuration consisted in using the same values of mass and angular velocity, but this time at Earth's gravity. This configuration was designed to determine if the gravity plays an important role on the wheel's performance on sand. The average results, after concluded both set of experiments, are shown in Fig. 3. It should be noted that in both configurations the angular velocity and mass were exactly the same, the only experimental parameter that changed was gravity.

Fig. 4 shows the average efficiency and maximum dispersion after 10 repetitions in the Earth and Mars configurations using the same wheel mass. Notice that the average and maximum dispersion values follow the same general shape, which corroborates that the peak in the efficiency reported for the Earth environment is experimentally sound.

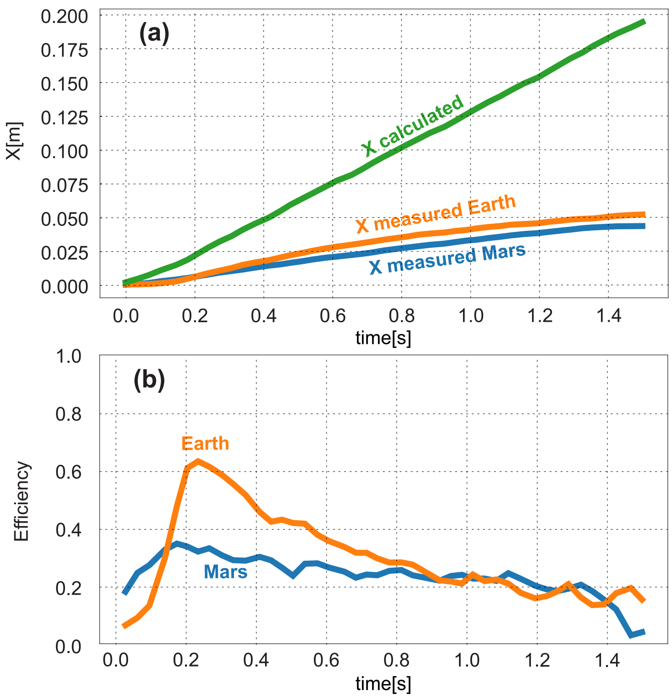

Figure 3. Rolling in Mars and in Earth ($\omega$ = 4 rad/s, m = 1.05 kg). (a) Temporal evolution of the averaged linear position, obtained by direct measurements processing the images (*x measured*) and by calculating using angular displacement (*x calculated*). (b) Temporal evolution of the averaged instantaneous efficiency (averages after 10 repetitions).

In Fig. 3, relevant changes are not observed in the wheel's general behavior. The biggest difference lies on the temporal evolution during the first 0.6 - 0.8 seconds of the motion. This departure between the two records may suggest that gravity plays some role when rolling over sandy soil. However, the observed differences might be caused by the trivial effect of the weight loss related to the gravitational difference. In order to determine if the differences observed in the experiments are truly related to different "intrinsic" behaviors in the granular media related to gravity, it is reasonable to compensate the mass difference causing the weight to be the same under both conditions.

If the wheel's mass on Mars is 1.05 kg, causing a 3.89 N weight, and we want the wheel to produce this same weight on Earth, its necessary to multiply the Mars's mass by the ratio between the gravities's accelerations of both planets. We obtain that the mass necessary for the Earth's experiments is of 0.4 kg.

Consequently, the mass of the wheel was reconfigured to be the one calculated before, guaranteeing constant weight for both experimental configurations. All other parameters were kept constant. Once more, 10 iterations (on Earth's gravity) were performed. The average results are shown in Fig. 5.

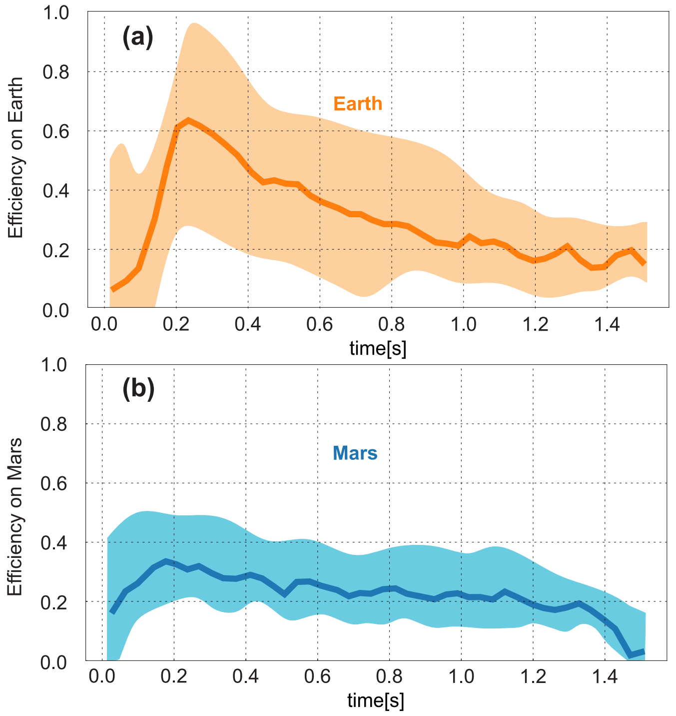

Figure 4. Rolling in Mars and in Earth ($\omega$ = 4 rad/s, m = 1.05 kg). In each case the average after 10 iterations is shown as a thin and darker curve. The clearer regions indicates the maximum dispersion found on the experiment's data. (a) Earth experiments, temporal evolution of the instantaneous efficiency. (b) Mars experiments, temporal evolution of the instantaneous efficiency.

Based on the data displayed in Fig. 5, we are able to conclude that the mobility performance of a wheel at different gravities is not a trivial consequence of the weight variation experienced due to gravitational reduction: there is a modification in the behavior of the granular medium associated to gravity that influences the rolling efficiency of the wheel, which confirms the findings of Kobayashi *et al.* [22]. A possible hypothesis to explain the similarities of the results found on the same mass experiments at different gravities, is that the modification of the interactions on the granular media gets compensated with the weight loss of the wheel. If the vertical penetration of the wheel during rolling is a key parameter to understand the motion, then these results are consistent with the observation of Altshuler *et al.* [23], who demonstrated that the maximum penetration depth of a sphere into granular media is independent of gravity, if the sphere conserved its mass in all gravities.

The Earth curves of Fig. 3 and 5 also reveal several interesting behaviors. Apparently there is a reduction of the rolling efficiency on Earth over time, that could be due to an increase of the wheel's burrowing on the granular media.

The Earth efficiency curves (orange line in Fig. 3b and 5b) are calculated using the data plotted on the green and orange curves of Fig. 3a and 5a respectively. In both cases, the measured linear displacement on Earth shown a non-linear behavior within the 0.1-0.3 s time interval. The peak found on the Earth efficiency curves, in a similar interval of time, is an unexplained effect.

When comparing the Mars and Earth efficiency curves, we appreciate that the Mars rolling efficiency behavior is much smoother, and despite it decreases slowly, the curve does not present any relevant irregularities.

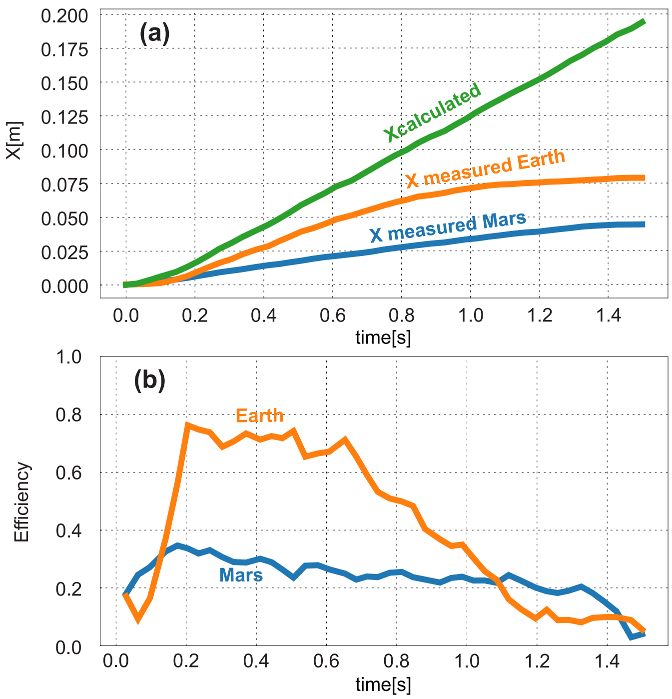

Figure 5. Rolling in Mars and in Earth ($\omega$ = 4 rad/s, w = 3.889 N). (a) Temporal evolution of the actual averaged linear position (10 iterations). (b) Temporal evolution of the averaged instantaneous efficiency (averages after 10 repetitions).

## IV. CONCLUSIONS

The rolling performance of a scaled-down Mars rover wheel on a granular bed was studied. Experiments were performed at two different gravitational conditions, Mars and Earth's. Two sets of experiments, performed at both gravitational conditions, were designed: equal angular velocity and mass of the wheel; equal angular velocity and weight of the wheel.

No substantial differences in the rolling efficiency were observed between both gravities if the wheel's mass is kept constant (except within the interval from 0.2 to 0.6 seconds). It can be qualitatively explained by the fact that the change of weight experienced by the wheel due to the lowering of gravity gets compensated with the loosening of the granular media.

A larger efficiency difference over a larger time is observed between Earth and Mars experiments when the wheel's mass is adjusted to compensate weight variations. It shows that the rolling performance does not depend on the change of weight of a vehicle. There may also be a modification on the particles interactions inside the granular media that may be causing a modification of the wheel's rolling efficiency. Further experimentation for quantifying other parameters that may be relevant, as the impact of changing the moment of inertia (separately from the role of gravity), are necessary to get more accurate conclusions.

In all experiments on Earth, a peak in the efficiency during the first moments of the motion was found. That is an unexpected behavior that we will study in more detail elsewhere. We also plan to perform future studies in a wider range of gravities, masses and angular velocities in order to see if the general tendencies in the efficiency reported here are maintained.

## REFERENCES

[1] Mars Exploration Rovers (2016). http://www.planetary.org/multimedia/space-images/spacecraft/diagram-of-a-curiosity-wheel.html. [Accessed March 12, 2019]

[2] I. Littleton and J. Hetherington, J. Terramechanics **15**, 95 (1978).

[3] A. Oida, A. Satoh, H. Itoh and K. Triratanasirichai, J. Terramechanics **28**, 319 (1991).

[4] B. Coutermarsh, J. Terramechanics **44**, 275 (2007).

[5] N. Taberlet, S.W. Morris and J.N. McElwaine, Phys. Rev. Lett. **99**, 68003 (2007).

[6] F.V. De Blasio and M.B. Saeter, Phys. Rev. E **79**, 22301 (2009).

[7] M. Gutierrez and A. Mohamed, Springer Ser. Geomech. Geoengin. **12**, 243 (2011).

[8] L. Ding, H. Gao, Z. Deng, K. Nagatani and K. Yoshida, J. Terramechanics **48**, 27 (2011).

[9] K.J. Burns, N.J. Balmforth and I.J. Hewitt, Proc. R. Soc. A Math. Phys. Eng. Sci. **473**, 20170375 (2017).

[10] P.A. Lemieux and D.J. Durian, Phys. Rev. Lett. **85**, 4273 (2000).

[11] P. By, J. Fluid Mech. **541**, 167 (2016).

[12] A. Rivera, K.E. Bassler, O. Ramos, A.J. Batista-Leyva, E.Altshuler and E. Martínez, Phys. Rev. Lett. **91**, 014501 (2003).

[13] E. Martínez, C. Pérez-Penichet, O. Sotolongo-Costa, O. Ramos, K.J. Måløy, S. Douady and E. Altshuler, Phys. Rev. E **75**, 31303 (2007).

[14] E. Altshuler, R. Toussaint, E. Martínez, O. Sotolongo-Costa, J. Schmittbuhl and K.J. Måløy, Phys. Rev. E **77**, 31305 (2008).

[15] R.A. Wilkinson, R.P. Behringer, J.T. Jenkins and M.Y. Louge, AIP Conf. Proc. **746**, 1216 (2005).

[16] V. Pletser, Acta Astronaut. **55**, 829 (2004).

[17] N. Callens, J. Ventura-Traveset, T.fL. De Lophem, C. Lopez De Echazarreta, V. Pletser and J.J. Van Loon, Microgravity Sci. Technol. **23**, 181 (2011).

[18] N. Murdoch, B. Rozitis, S.F. Green, T.L. De Lophem, P. Michel and W. Losert, Granul. Matter **15**, 129 (2013).

[19] U. Kaczmarczik, H.J. Rath and P. von Kampen, Acta Astronaut. **59**, 278 (2006).

[20] D.I. Goldman and P. Umbanhowar, Phys. Rev. E **77**, 21308 (2008).

[21] C. Sunday, N. Murdoch, O. Cherrier, S. Morales Serrano, C. Valeria Nardi, T. Janin, I. Avila Martinez, Y. Gourinat and D. Mimoun, Rev. Sci. Instrum. **87**, 84504 (2016).

[22] T. Kobayashi, Y. Fujiwara, J. Yamakawa, N. Yasufuku and K. Omine, J. Terramechanics **47**, 261 (2010).

[23] E. Altshuler, H. Torres, A. González-Pita, G. Sánchez-Colina, C. Pérez-Penichet, S. Waitukaitis and R.C. Hidalgo, Geophys. Res. Lett. **41**, 3032 (2014).

[24] J.Y. Wong and T. Kobayashi, J. Terramechanics **49**, 349 (2012).

[25] H. Nakashima and T. Kobayashi, J. Terramechanics **53**, 37 (2014).

[26] G. Viera-López, A. Serrano-Muñoz, J. Amigó-Vega, O. Cruzata and E. Altshuler, Rev. Sci. Instrum. **88**, 86107 (2017).

[27] Diagram of a Curiosity wheel. http://www.planetary.org/multimedia/space-images/spacecraft/diagram-of-a-curiosity-wheel.html. [Accessed March 12, 2019]

---