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# Dynamic Rocker-Bogie: A Stability Enhancement for High-Speed Traversal

**Hong-an Yang, Luis Carlos Velasco Rojas*, Changkai Xia, Qiang Guo**
School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an, China

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**ABSTRACT**

The rocker-bogie suspension mechanism it's currently NASA's favored design for wheeled mobile robots, mainly because it has robust capabilities to deal with obstacles and because it uniformly distributes the payload over its 6 wheels at all times. Even though it has many advantages when dealing with obstacles, there is one major shortcoming which is its low average speed of operation, making the rocker-bogie system not suitable for situations where high-speed traversal over hard-flat surfaces is needed to cover large areas in short periods of time, mainly due to stability problems. This paper proposes to increase the stability of the rocker-bogie system by expanding its support polygon, making it more stable and adaptable while moving at high speed, but keeping its original robustness against obstacles: One rocker-bogie system, two modes of operation.



***Corresponding Author:***

Luis Carlos Velasco Rojas
School of Mechanical Engineering,
Northwestern Polytechnical University,
No 127 Youyi Xilu, Xi'an, Shaanxi Province, P. R. China.
Email: velasco.luisc@gmail.com

## 1. INTRODUCTION

There is an increasing need for mobile robots which are able to operate in unstructured environments with highly uneven terrain. These robots are mainly used for tasks which humans cannot do and which are not safe. In order to achieve these tasks, any mobile robot needs to have a suitable mobile system according to each situation. Among these mobile systems, it's the rocker-bogie suspension system that was first used for the Mars Rover Sojourner and it's currently NASA's favored design for rover wheel suspension.

The rocker-bogie suspension is a mechanism that, along with a differential, enables a six-wheeled vehicle to passively keep all six wheels in contact with a surface even when driving on severely uneven terrain. There are two key advantages to this feature. The first advantage is that the wheels' pressure on the ground will be equilibrated. This is extremely important in soft terrain where excessive ground pressure can result in the vehicle sinking into the driving surface. The second advantage is that while climbing over hard, uneven terrain, all six wheels will nominally remain in contact with the surface and under load, helping to propel the vehicle over the terrain. Exploration rovers take advantage of this configuration by integrating each wheel with a drive actuator, maximizing the vehicle's motive force capability [1].

One of the major shortcomings of current rocker-bogie rovers is that they are slow. In order to be able to overcome significantly rough terrain (i.e., obstacles more than a few percent of wheel radius) without significant risk of flipping the vehicle or damaging the suspension, these robots move slowly and climb over the obstacles by having wheels lift each piece of the suspension over the obstacle one portion at a time [2]. While performance on rough terrain obstacles is important, it should be also considered situations where the surface is flat or it has almost imperceptible obstacles, where the rover should increase its speed to arrive faster from point A to point B.

In this paper, the authors propose modifications in the structure of the rocker-bogie system increasing the span of the support polygon in pursuance of achieving a greater stability margin over high-speed traversal without losing the original configuration.

## 2. RESEARCH METHOD

NASA 's most modern rover, the Mars Rover Curiosity (MRC), gives us proven information that demonstrates the efficiency of rocker-bogie systems dealing with obstacles the size of the diameter of its wheels, but moving at an average speed below 2 cm/s to ensure stability against overturning due to sudden changes in the position of the center of gravity. Similarly, studies obtained with the MRC show that the maximum speed on hard, flat ground is 4 cm/s, also having as main limiting condition the position of the CoG and its influence on the stability margin of the system [3].

This is where the question that motivates this research arises: what can be done to increase the stability of the rocker-bogie system in situations requiring transfers at high speed?The proposed solution is the result from a previous study of the factors that rule the stability of an n wheels vehicle, concluding that the area of the vehicle (wheels) that is in contact with the ground has great influence on the displacement of the CoG and therefore on the stability margin of the vehicle.

In order to present and analyze the proposed dynamic rocker-bogie system, the criteria used and a series of experiments and simulations are presented in the following parts of this document.

### 2.1. Stability Margin

Applications of high-speed robots cover exploration, reconnaissance, and material delivery, both military and civilian. These systems are designed to operate on natural terrain that may be sloped, slippery, deformable, uneven, flat or hard. Unfortunately, these systems are susceptible to rollover while moving at high speed or performing severe maneuvers, especially in the rocker-bogie system, where its design was merely focused on slow speed traversal over obstacles. Despite the fact that many systems are designed with rugged chassis (and some are designed to be invertible), rollover accidents or abrupt perturbations in the transfer load often disable the robot and/or damage its payload [4].

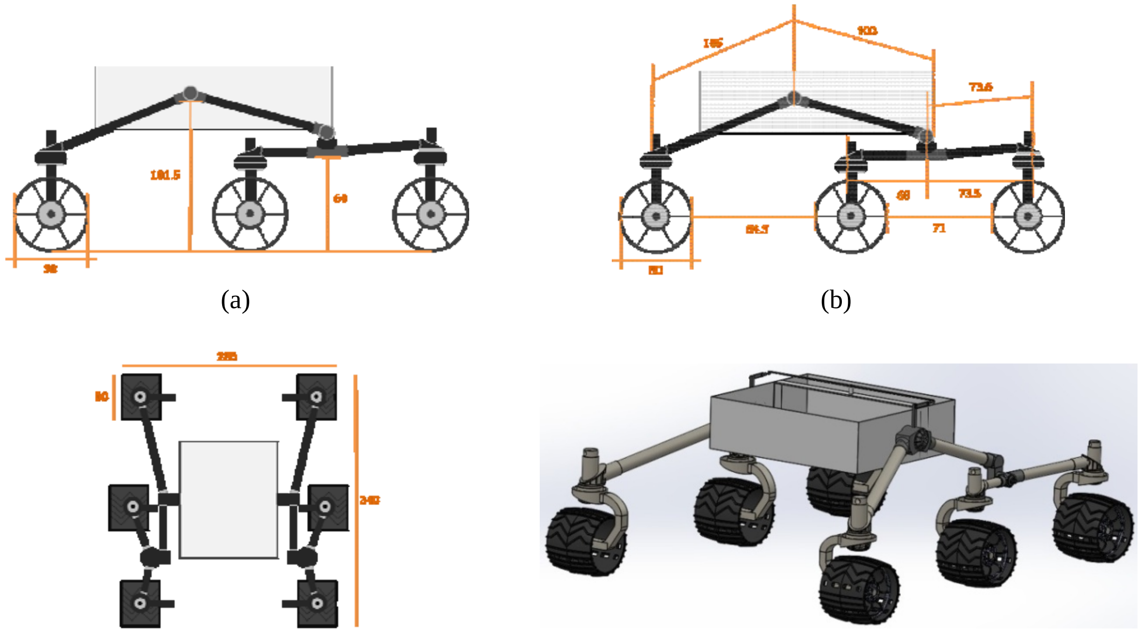
The National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation of the United States government has used various metrics and driving maneuvers to characterize the rollover resistance of vehicles in particular situations. Metrics are usually measurements of dimensional, mass and inertial properties of vehicles or calculations combining these properties in ways intended to represent rollover resistance. Each of these indicators of rollover resistance has both advantages and disadvantages, and several would be acceptable candidates for comparative scientific information. The agency favors static stability factor because it is applicable to both induced and accidental rollover. The causal basis for its good correlation to crash outcomes is clear. It is relatively simple to understand and can be measured inexpensively with good accuracy and repeatability [5].

The Static Stability Factor (SSF) of a vehicle is one half the track width, TW, divided by h, the height of the center of gravity above the road. The inertial force which causes a vehicle to sway on its suspension (and roll over in extreme cases) in response to cornering, rapid steering reversals or striking a tripping mechanism, like a curb, when sliding laterally may be thought of as a force acting at the CoG to pull the vehicle body laterally. A reduction in CoG height increases the lateral inertial force necessary to cause rollover by reducing its leverage, and the advantage is represented by an increase in the computed value of SSF. A wider track width also increases the lateral force necessary to cause rollover by increasing the leverage of the vehicle's weight in resisting rollover, and that advantage also increases the computed value of SSF. The factor of two in the computation "TW over 2h" makes SSF equal to the lateral acceleration in g's (g-force) at which rollover begins in the most simplified rollover analysis of a vehicle represented by a rigid body without suspension movement or tire deflections [5].

This approach will be used to perform the stability analysis of the proposed system later in Section 3 of this document.

### 2.2. Design Modifications

In order to analyze the proposed ideas, the Mars Rover Curiosity is used as a geometrical model to design the suggested dynamic rocker-bogie system. For simulation purposes the dimensions of the studied rover are described in Figure 1. The lateral view shows in (a) and (b) the lengths and heights of the model, while the top view in (c) shows the horizontal and vertical distances between the wheels contacts points. All the dimensions are expressed in centimeters (cm). Finally, an isometric view of the 3D CAD model is showed in (d).



(a) (b)

(c) (d)

Figure 1. Dynamic rocker-bogie simulation model dimensions

#### 2.2.1. Dynamic Bogie Modifications

Acknowledging that one way to increase the stability margin of a rover with rocker-bogie system is to expand the area in contact with the ground (Support Polygon), it's necessary to analyze how to make this possible without completely altering the original operation scheme of the rocker-bogie suspension.

As mentioned in Section 2.1, a simple but useful metric is the Static Stability Factor (SSF), which is computed as the ratio of the lateral position of the vehicle CoG to the vertical position (see Figure 2). Larger values of SSF indicate greater stability. Physically, the SSF corresponds to the lateral acceleration in g's that causes wheel lift-off for a rigid vehicle traversing flat ground [4].

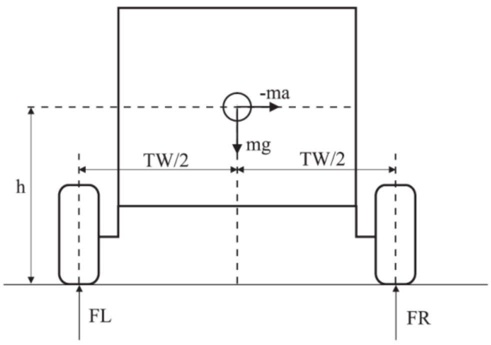



Figure 2. Static Stability Factor diagram

$$SSF = TW / 2h \qquad \text{Equation 1.}$$

Several metrics based on geometric principles have been developed for stability measurement. Researchers in mobile robotics have recognized that the location of the CoG relative to the wheel–terrain contact points is critical to vehicle stability [1]. The support polygon is defined as the convex hull of the polygon formed by wheel–terrain contact points projected onto a horizontal plane. An early geometric measure defined stable vehicle configurations as those where the horizontal projection of the vehicle CoG lies within this polygon. A stability margin was then defined based on the shortest distance from the projected CoG to a side of the polygon.

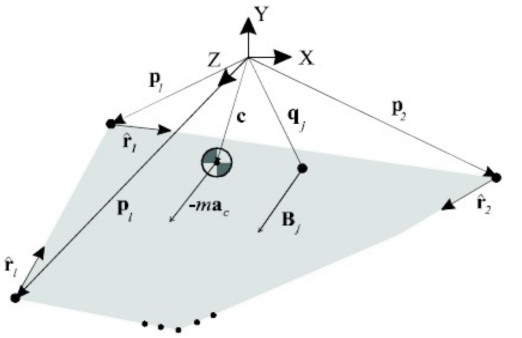



Figure 3. Support polygon for a general robot

In this approach, the robot's n wheel-terrain contact points $p_i$ , i={1,…,l} are numbered in ascending order in a clockwise manner when viewed from above, as shown in Figure 3. These points form the nodes of a three-dimensional support polygon. The lines joining the wheel-terrain contact points are referred to as tipover axes and are denoted $r_i$ [4].

After an analysis, the authors introduce a possible solution that meets the conditions laid down, which is based on adding a rotation axis over the Y-plane of the bogie system, varying the yaw orientation of the bogie, thereby altering the position of the outer support polygon points and increasing the size of the area in contact with the ground (Figure 4).

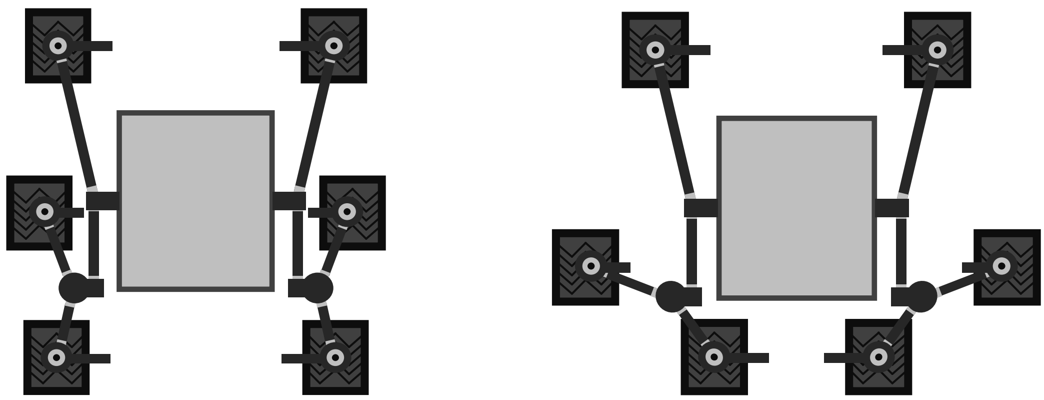



Figure 4. Dynamic bogie modifications: (a) Rocker-bogie regular configuration, (b) Rocker-dynamic bogie high speed configuration

The proposed system includes rotation motors for each wheel that are in charge of the translation of the rover, also, it uses an extra motor on each wheel to change its orientation and therefore change the orientation of the rover. In addition it controls the added bogie rotation axis with a motor that allows the movement of each bogie when it's needed.

Using Equation 1, different rotation angles about the new axis are analyzed, seeking to find a suitable value in which the suspension provided by the rocker-bogie system is not compromised and the expansion of the contact polygon is expanded achieving an optimal SSF (see Table 1).

Table 1. Static Stability Factor variation due to increase of support polygon area

| | **Rotation degree** | **TW [cm]** | **h [cm]** | **SSF** |
|---|---|---|---|---|
| 1 | 10.0 | 295.5 | 110.0 | 1.34 |
| 2 | 20.0 | 309.0 | 110.0 | 1.40 |
| 3 | 35.0 | 338.5 | 110.0 | 1.54 |
| 4 | 45.0 | 340.0 | 110.0 | 1.55 |

At first glance we assume 45 degrees as the optimal rotation factor in the dynamic bogie design because the criteria in Equation 1 shows a favorable increase in the SSF, considering this rotation angle as the maximum possible without altering the original rocker-bogie performance. These values will be proven efficient later in Section 3 of this paper.

The proposed Dynamic rocker-bogie (DRB) has a traditional configuration with a robust performance when moving through surfaces with obstacles, and it also has the ability to increase its contact points polygon whenever high-speed traversal is needed. This change in configuration is accomplished after a transformation using the dynamic bogie, achieving a high-speed mode: One rocker-bogie system, two modes of operation.

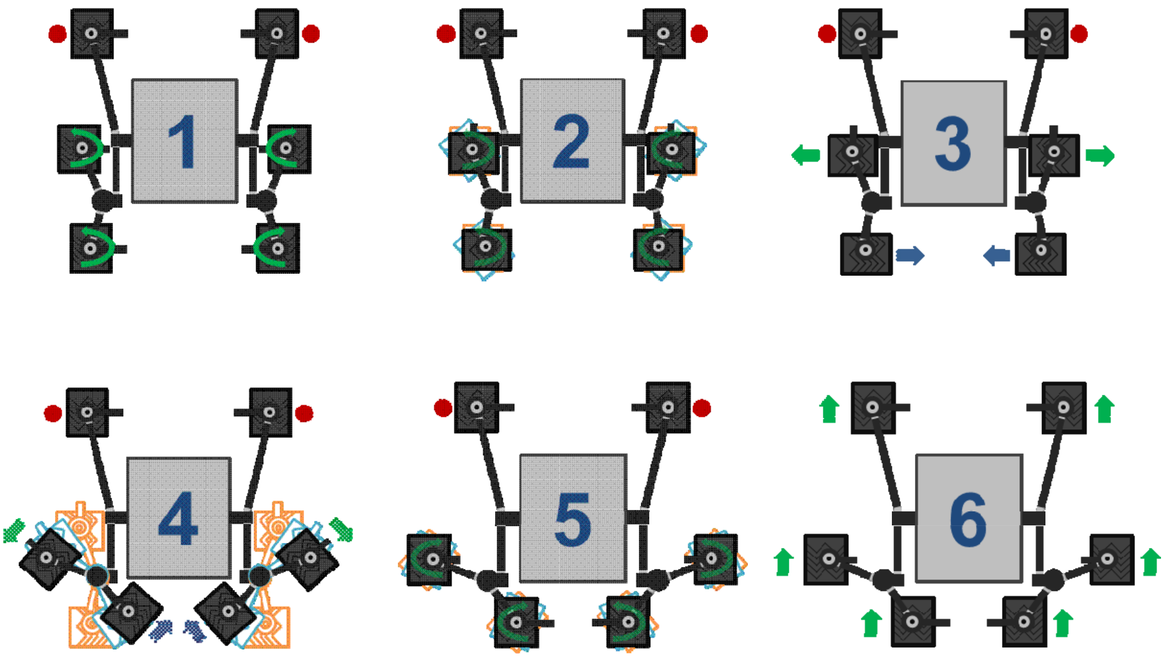



Figure 5. Dynamic rocker-bogie transformation sequence

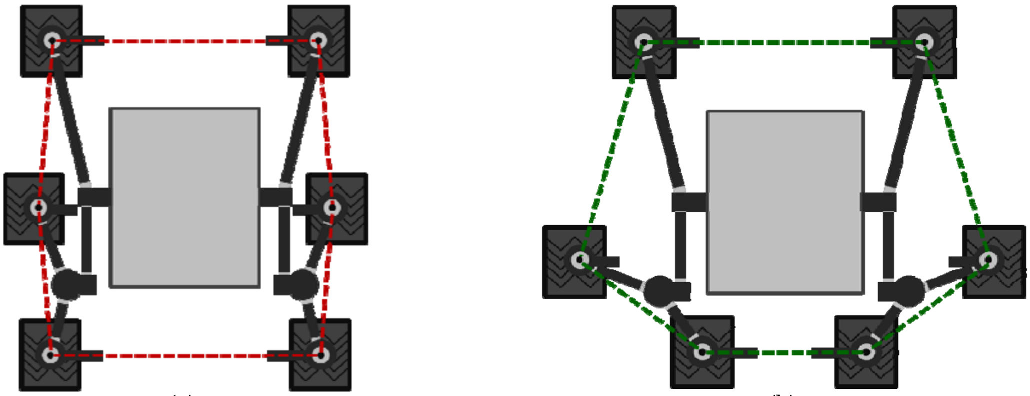
The transformation sequence that allows the DRB to switch from a traditional rocker-bogie configuration to the proposed high-speed mode is described in Figure 5, where the order of the sequence is defined by the numbers showed in the body of the rover.

The first step in the sequence is to stop the front wheels locking the rover's position in order to proceed with the transformation steps. Next the middle and rear wheels rotate 90 degrees swinging out from the original position. After this, the expansion of the polygon support begins by spinning the middle wheels towards the exterior of the rover and the rear wheels towards the interior of it, at the same time the motors that control the bogie rotation axis detect the applied force by the rotation of wheels and start rotating the 45 degrees calculated in Table 1. Once the 45 degrees rotation of the bogie is completed, the wheels return to their original position facing forward, and the rover is ready to start its high-speed mode traversal.

### 2.2.2. Support Polygon Expansion

As it was explained before in this paper, the authors aim to increase the stability margin of the rocker-bogie system by expanding its support polygon considering that's important to preserve the native suspension performance of the original design of this system.

Therefore, once the system has rotated its bogies 45 degrees to the required high-speed mode position, the rover's support polygon is expanded reaching a bigger contact area as showed in Figure 6.



(a) (b)

Figure 6. DRB Support polygon expansion: (a) Rocker-bogie traditional robust obstacle traverse configuration, (b) Rocker-bogie high-speed traversal configuration

This expansion of the contact area size sets the rover's CoG inside a bigger track base, making it more robust against load transfers due to the interaction of internal and external forces such as g-forces and inertia moments.

## 3. RESULTS AND ANALYSIS

In this section of the document, the results of the analysis performed using the Static Stability Factor (SSF) metric introduced in [5] are presented, showing the stability margin improvement of the high-speed mode compared with the traditional configuration of the rocker-bogie system.

Also, a model of the proposed system was developed in Solidworks, and using its multibody dynamic motion analysis it was possible to appreciate the performance of both modes of the dynamic rocker-bogie system, thus data obtained of this simulations will be contrasted with the SM metric results.

### 3.1. Stability Moment

As explained in Section 2.2.1, the proposed system has two operating modes, each with different SSF values. The traditional rocker-bogie configuration has a narrower span in its polygon support (see Figure 7).

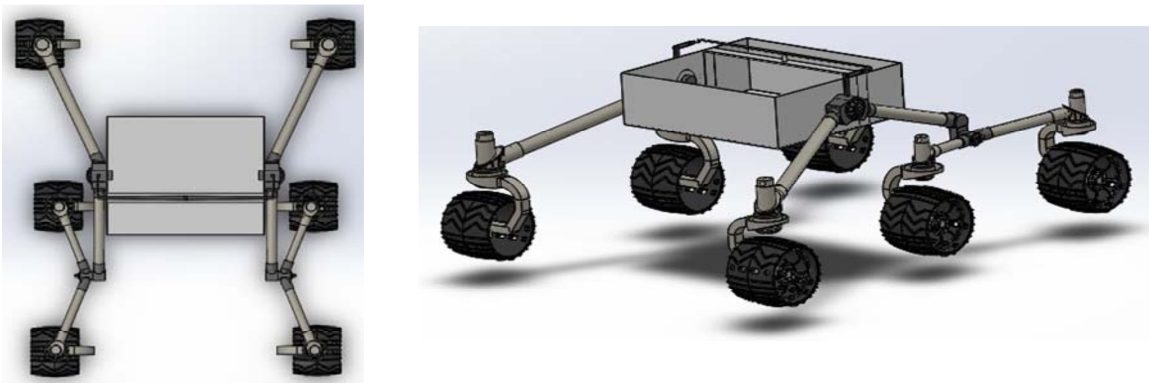


Figure 7. Dynamic rocker-bogie traditional robust obstacles traverse configuration Solidworks model

The SSF calculation for the Dynamic rocker-bogie traditional robust obstacle traverse configuration was done as follows:

TW = 285 cm.

h = 110 cm.

SSF = TW / 2h = 285 / (2*110) = 1.295.

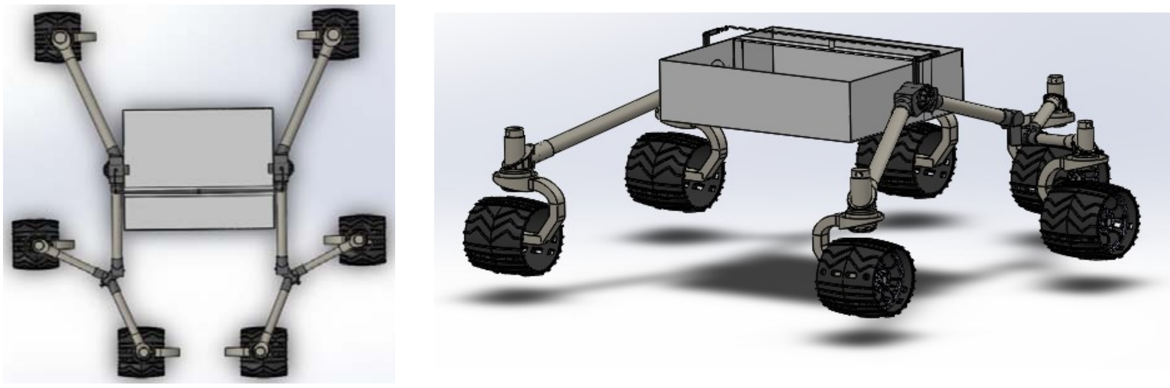


Figure 8. Dynamic rocker-bogie high-speed traversal configuration Solidworks model

Following the same criteria, the Rocker-bogie high-speed traversal configuration (see Figure 8) was subjected to the same SSF analysis:

TW = 340 cm.

h = 110 cm.

SSF = TW / 2h = 340 / (2*110) = 1.545.

These results show that like expected, the DRB design increases the stability margin of the rover, by a 16.2% for the given dimensions of the studied model. This increase can be determinant if the rover is moving at high speed and it encounters an obstacle too close to be avoided.

**3.2. Dynamic Rocker-Bogie Simulations**

As mentioned in Section 2, the Mars Rover Curiosity has an average top speed of 4 cm/s, which the authors consider not fast enough when a flat-hardened surface is present and the rover needs to reach a destination without dealing with any significant obstacle, thus, for the realized simulations a higher speed considered a feasible approach to the situation of “high-speed traversal” is used: 262 cm/s.

In this section, the results of the realized simulations are presented, analyzing and comparing the disturbances in the rover’s Center of Gravity position in each of the two operating modes, contrasting the response of these two different configurations of the rocker-bogie system against trivial obstacles that can be present along the high-speed traversal surface. The test track used for these experiments is a 10x30 meters platform with two cylindrical bumpers with the height of half the wheel’s. The simulated rover has a total mass of 305 Kg.

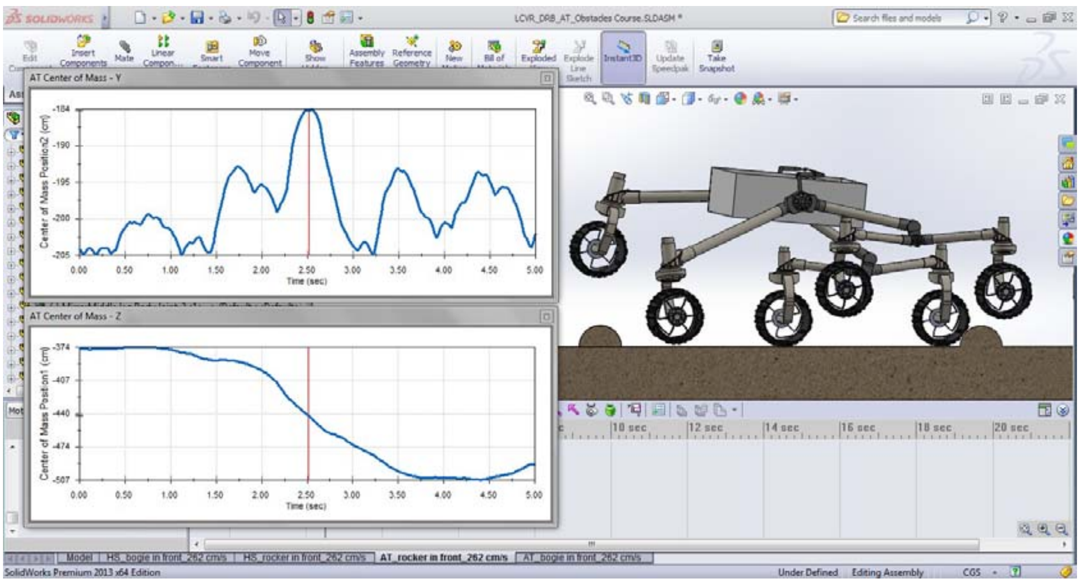



Figure 9. Dynamic rocker-bogie traditional robust obstacles traverse configuration Solidworks simulation

The first set of obtained results shows how the rover's CoG changes position constantly and violently, having a tough impact in the payload and increasing the possibilities of having a roll over situation while moving at high-speeds and encountering a common obstacle (rock, slope, etc.) using the traditional rocker-bogie configuration. (See Figure 9).

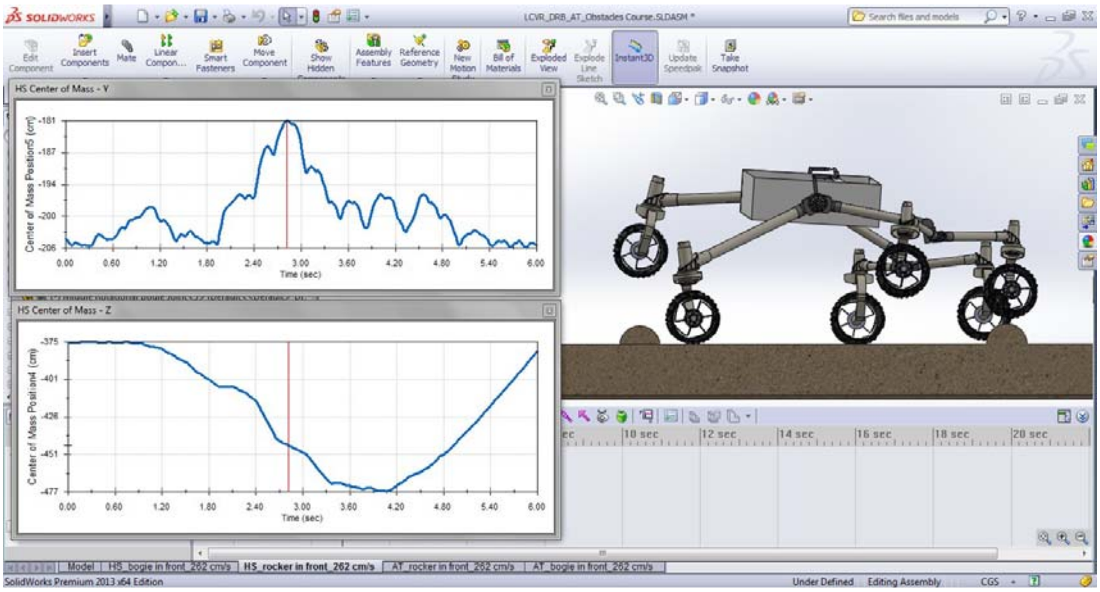


Figure 10. Dynamic rocker-bogie high-speed traversal configuration Solidworks simulation

On the other side, the results of the high-speed traversal configuration show that, even though there's still constant changes in the rover's CoG position, the impact on the payload it's more equalized over time, not having the tough impact seen in the traditional rocker-bogie configuration, thus making it more stable if it encounters a common obstacle (rock, slope, etc.) while moving at high-speed over a hard-flatten surface.

With the realized simulations, the authors are convinced that the proposed modifications on the traditional rocker-bogie design make a significant increase in the rover's stability in situations where it needs to move through distances over uniform surfaces and facing traversable obstacles at any given time.

## 4. CONCLUSION

The present paper proposed a novel design in pursue of increasing the rocker-bogie mobility system behavior when high-speed traversal is required. This situation was faced presenting two modes of operation under the same working principle, a rocker-bogie system with a robust obstacles traverse features and an expanded support polygon achieved by rotating the bogies of each side of the vehicle. This increase in the stability margin was proved contrasting the SSF metric with the 3D model simulations done in Solidworks, showing that at high-speeds the expanded support polygon equalizes the payload transfer stabilizing it against fierce changes in the rover's center of gravity.

Even though the robustness against obstacles while moving at high-speeds was slightly increased, the authors suggest further research analyzing the dynamic behavior of every member of the system to continue roving the efficiency of the proposed Dynamic Rocker-bogie system. Also, field experimentation using a prototype is highly suggested in order to analyze the results obtained in the calculations and simulations, and the behavior of a real model.

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## BIOGRAPHIES OF AUTHORS

Hong-an Yang, Ph.D, is an Associate Professor in the School of Mechanical Engineering at the Northwestern Polytechnical University. He received his Ph.D. with a major in Mechanical Manufacturing and Automation in 2004. He was a visiting scholar in the University of Texas at San Antonio, USA from Feb 2010 to Feb 2011. Dr. Yang specializes in the study of stochastic simulation optimization problems, mobile robotic vehicles and job shop scheduling problems.

Luis Carlos Velasco Rojas, M.Sc, is an Electronic Engineer graduated from the Military School of Engineering in La Paz, Bolivia. His research field is biomimetics with a specialization in swarm robotics and unmanned vehicles. Mobile robotics has always been his passion, and this is why he's currently coursing a Masters Degree program in the field of Mechatronics at the Northwestern Polytechnical University, researching innovative mobility systems for unmanned vehicles and swarm behavior algorithms for multirobot systems.

Changkai Xia, M.Sc, comes from Mechanical and Electronic Engineering, Northwestern Polytechnical University, China. His areas of research interest are robotics, automation manufacturing, and stochastic simulation optimization.He holds a bachelor's degree in Mechanism design, manufacturing and automatization. During his undergraduate, he also finishes some secondary developments to 3D design software. Recently, he works on a variety of control of robotics and projects, which are closely related to stochastic simulation optimization.

Qiang Guo, M.Sc., comes from Mechanical and Electronic Engineering, Northwestern Polytechnical University, China. His areas of research interest are robotics, automation manufacturing, and stochastic simulation optimization.
He holds a bachelor's degree in Mechanical engineering and automation. He is working on design of mechanical structure, robot control, and a variety of simulation optimizations From undergraduate to now.