International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

Design and development of a rocker-bogie mechanism robot with integrated environmental sensors

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International Journal of Science and Research Archive, 2024, 12(02), 1768–1778

Publication history: Received on 24 June 2024; revised on 04 August 2024; accepted on 07 August 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.12.2.1440

Abstract

Today, the importance of rovers in exploring our solar system is universally acknowledged. These specialized vehicles are crafted mainly for missions that explore the surfaces of celestial bodies like Mars and the Moon, focusing on the geological analysis of rocks and soil. The harsh environmental conditions, climatic fluctuations, and communication challenges necessitate rovers to possess both high-speed and long-range capabilities within constrained mission timelines. Although significant advancements have been made, the slow operational speed continues to be a major challenge, despite the widespread use of various mechanisms in mobile robotics.

This study unveils a novel suspension mechanism and details its kinematic analysis results. Unlike the traditional rocker-bogie suspension system, developed in the late 1990s for effective weight distribution across diverse terrains, our new design significantly improves protection against rollovers during high-speed linear bogie movements. This enhancement boosts operational reliability in field environments, enabling quicker exploration while preserving the obstacle traversal capabilities of the rocker-bogie system. Sensor data is relayed to an Internet of Things (IoT) cloud service called Thingspeak for real-time monitoring and research. Additionally, a weather monitoring system powered by an Arduino chip provides live updates on atmospheric pressure, temperature, humidity, air quality, and light intensity at the rover's location.

Keywords: Mars Rover; Mobility System; NASA; Rocker-Bogie; Mechanism; Environmental Sensors

1. Introduction

The exploration of planetary surfaces within our solar system has become a cornerstone of contemporary space missions, motivated by the quest to uncover the geological and potentially biological histories of celestial bodies like Mars and the Moon. These explorations aim to answer fundamental questions about the formation and evolution of our solar system and to search for signs of past or present life beyond Earth. Central to these missions are rovers, the primary robotic vehicles tasked with navigating the diverse and often treacherous terrains of these distant worlds. Rovers are engineered to move across the surface, overcoming obstacles such as rocks, craters, and slopes while performing detailed scientific investigations. Their instruments analyze the composition of rocks and soil, measure atmospheric conditions, and search for signs of water or other elements critical to life. However, executing these missions is fraught with numerous challenges. The harsh environmental conditions of planets like Mars, which include extreme temperatures, dust storms, and high radiation levels, pose significant threats to the rovers' functionality and longevity. Climatic variations, such as seasonal changes and daily temperature fluctuations, further complicate the operational stability of these vehicles. Moreover, the vast distances between Earth and these celestial bodies introduce stringent communication constraints. There are significant delays in transmitting commands and receiving data, often ranging from several minutes to hours, depending on the planetary position relative to Earth. This delay necessitates a high degree of autonomy in rover operations, as real-time control is not feasible. Despite significant advancements in

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rover technology over the past few decades, one persistent challenge remains: the slow operational speed of these vehicles. Current rovers are designed to move cautiously to avoid hazards and ensure precise scientific measurements, but this slow pace limits the overall efficiency and scope of the missions. With mission durations often constrained by the lifespan of the rovers' power sources and the harshness of the environment, the need for higher speed and more efficient exploration becomes paramount. Enhancing the speed of rovers without compromising their ability to navigate difficult terrain and perform scientific tasks is a complex engineering problem. Innovative suspension mechanisms, more robust navigation algorithms, and advanced power systems are among the potential solutions being explored to address this challenge. Improving the operational speed of rovers would not only increase the area they can cover within their operational lifespan but also enhance the timeliness and breadth of the scientific data collected, thereby maximizing the scientific return of these ambitious space missions.

The traditional rocker-bogie suspension system, first introduced in the late 1990s, represents a significant milestone in the design of planetary exploration rovers. This suspension mechanism has been widely adopted in various space missions, including NASA's Mars rovers, due to its effective weight distribution and ability to negotiate diverse and challenging terrains. The rocker-bogie suspension system consists of two primary components: the rocker arms and the bogie arms. The rocker arms are connected to the rover’s chassis, while the bogie arms are attached to the rocker arms. This configuration allows the rover to maintain stable contact with the ground even when traversing uneven or rocky surfaces.

The key features of the rocker-bogie system include:

- *Independent Suspension:* Each wheel is mounted on a separate rocker arm, allowing independent movement and ensuring that the rover can adapt to varying terrain heights.
- *Effective Weight Distribution:* The system distributes the rover's weight across multiple wheels, which helps in reducing the impact on any single wheel and enhances the rover’s ability to manage obstacles.
- *Obstacle Negotiation:* The articulated design of the rocker-bogie system allows the rover to climb over obstacles such as rocks and small craters without getting stuck.

The success of the rocker-bogie suspension system is evident from its extensive use in several high-profile missions. For instance, NASA’s Mars rovers, such as Spirit, Opportunity, and Curiosity, have utilized this system to traverse the Martian surface. The ability of the rocker-bogie system to handle rough terrain and provide a stable platform for scientific instruments has made it a preferred choice for planetary exploration. Despite its advantages, the rocker-bogie suspension system has notable limitations, particularly in maintaining stability and preventing rollovers during high-speed movements. While the rocker-bogie system is highly effective for slow, deliberate navigation over uneven surfaces, its performance declines when the rover needs to move quickly. The system, designed for stability at low speeds, struggles to provide adequate support during rapid traversal, increasing the risk of rollovers, especially on sloped or uneven terrain. As a result, the cautious navigation required to avoid rollovers limits the rover's speed, thereby constraining the exploration range and the efficiency of scientific operations. This becomes especially problematic for missions with time-sensitive goals or those requiring extensive surface coverage. As exploration missions continue to advance, there is an increasing demand for rovers capable of higher speeds while maintaining or even enhancing their terrain navigation and analytical capabilities. This growing need underscores the importance of developing innovative suspension mechanisms that offer greater stability at higher speeds, effectively manage forces that could lead to rollovers, and enable faster operation without compromising the ability to traverse obstacles or conduct scientific tasks. Moreover, any new suspension system must preserve or improve adaptability to various terrains, including rocky, sandy, and uneven surfaces, to ensure robust and versatile performance across different exploration environments.

2. Literature Review

The rocker-bogie suspension system, developed by NASA in the late 1990s, has been a cornerstone in the design of planetary rovers. This system features a combination of rocker arms and bogie arms that distribute the rover's weight and enhance its ability to traverse rough terrain. The rocker-bogie system’s primary advantage is its ability to keep all wheels in contact with the ground, thereby improving traction and stability over uneven surfaces (NASA, 2007). This design has been utilized in various Mars rovers, including the Spirit and Opportunity rovers, where it demonstrated effective obstacle negotiation and weight distribution (Smith et al., 2004). Despite its successes, the rocker-bogie system has limitations, especially concerning stability during high-speed movements. The system is optimized for low-speed operation, which can lead to issues with rollover risk when the rover moves rapidly over uneven terrain (Johnson et al., 2010).

These stability concerns have been highlighted in several studies, indicating that while the system is effective for slow traversal, its performance deteriorates under high-speed conditions (Wilson & Miele, 2012). Recent advancements in suspension technology aim to address the limitations of traditional systems like the rocker-bogie. Researchers have proposed various innovative designs to improve rover stability and speed. For example, the use of active suspension systems, which adjust the suspension configuration in real-time based on terrain conditions, has shown promise in enhancing both stability and speed (Garcia et al., 2016). These systems use sensors and algorithms to adapt the rover's suspension to changing terrain, potentially reducing the risk of rollovers during high-speed operations. Another approach involves the development of advanced materials and designs that can provide better shock absorption and stability. Researchers have explored the use of adaptive materials and smart actuators that can dynamically adjust their properties based on environmental feedback (Lee et al., 2018). These innovations aim to improve the rover’s performance on a wider range of terrains while maintaining high-speed capabilities. The integration of environmental sensors into rover systems has become increasingly important for enhancing mission capabilities. Environmental sensors can provide real-time data on atmospheric conditions, terrain properties, and other factors that influence rover performance. Studies have shown that incorporating sensors such as barometers, thermometers, and humidity sensors can significantly improve the rover’s ability to adapt to changing conditions (Chen et al., 2019).

Figure 1 NASA’S Curiosity Mars Rover

This real-time data allows for more informed decision-making and adjustments to the rover's operation, thereby increasing overall mission efficiency. The use of Internet of Things (IoT) technologies for real-time data transmission and monitoring has also been explored. IoT platforms, such as Thingspeak, enable continuous data collection and remote monitoring, facilitating more effective mission management and research (Kumar et al., 2021). By leveraging IoT technologies, researchers can enhance the rover’s ability to collect and analyze environmental data, leading to more accurate and timely scientific observations. Despite the advancements in rover suspension systems and environmental monitoring, several challenges remain. The need for higher speed and improved stability continues to drive research and development efforts. Future work in this area will likely focus on integrating new suspension technologies with advanced sensor systems to create more versatile and efficient rovers. Additionally, addressing the trade-offs between speed, stability, and obstacle negotiation will be crucial for achieving the goals of upcoming exploration missions (Martinez et al., 2023). Recent advancements in planetary rover technology emphasize the integration of sophisticated suspension systems and environmental sensors to enhance exploration capabilities. Zhou, Yang, and Li (2022) provide a comprehensive review of the current developments and future directions in integrating environmental sensors into planetary rovers, highlighting the crucial role these sensors play in real-time data collection and mission success (Zhou, Yang, & Li, 2022). Pinto, Pereira, and Oliveira (2018) discuss the design and implementation of a hybrid suspension system that combines the advantages of various mechanisms to improve rover performance on diverse terrains (Pinto, Pereira, & Oliveira, 2018). Advanced sensor technologies, such as those detailed by Barker, Smith, and Wilson (2020), are critical for enhancing the rover’s ability to gather and analyze environmental data, thereby supporting autonomous operations and scientific research (Barker, Smith, & Wilson, 2020). Kowalski, Patel, and Thompson (2021) review recent advancements in high-speed navigation and stability for planetary rovers, focusing on overcoming the challenges associated with rapid traversal and maintaining stability (Kowalski, Patel, & Thompson, 2021).

Nguyen, Lee, and Choi (2022) present case studies and simulations demonstrating how adaptive suspension systems can significantly enhance rover performance by improving adaptability to various terrains (Nguyen, Lee, & Choi, 2022). Jiang, Chen, and Wu (2020) introduce a novel suspension mechanism designed to address the limitations of traditional systems, aiming to enhance rover stability and performance (Jiang, Chen, & Wu, 2020). Real-time environmental monitoring and data analysis using IoT technologies, as explored by Khan, Aslam, and Ali (2021), are essential for ensuring the effectiveness of exploration missions (Khan, Aslam, & Ali, 2021). Xu, Zhang, and Wang (2022) focus on the simulation and optimization of high-speed suspension systems, highlighting strategies to improve rover mobility and efficiency (Xu, Zhang, & Wang, 2022). The impact of environmental sensors on rover autonomy and mission success is discussed by Miller, Clark, and Turner (2020), emphasizing their importance for mission planning and execution (Miller, Clark, & Turner, 2020). Alvarez, Moreno, and Diaz (2019) contribute to the field by presenting the design and development of a modular suspension system that offers flexibility and robustness for planetary rovers (Alvarez, Moreno, & Diaz, 2019). Kumar, Patel, and Choudhury (2021) explore dynamic modeling and control strategies to improve the stability and performance of rover suspension systems, providing valuable insights into system optimization (Kumar, Patel, & Choudhury, 2021). The literature on the design and development of rocker-bogie mechanism robots with integrated environmental sensors highlights significant progress and ongoing challenges in optimizing rover performance for planetary exploration. Anderson and Smith (2019) underscore the importance of high-performance suspension systems, noting both innovations and challenges in achieving effective mobility and stability in extra-terrestrial environments (Anderson & Smith, 2019). Brown and Zhao (2020) contribute insights into new suspension mechanisms, emphasizing their potential to enhance rover capabilities across varied terrains (Brown & Zhao, 2020). Carter and Williams (2021) discuss advancements in rover suspension systems, focusing on improving exploration efficiency and obstacle negotiation (Carter & Williams, 2021). The integration of environmental sensors is further explored by Davis and Thomas (2021), who demonstrate how real-time data collection enhances autonomous operation (Davis & Thomas, 2021). Innovative designs by Foster and Lee (2022) and adaptive control algorithms by Green and Patel (2020) reveal significant strides in enhancing rover mobility and stability (Foster & Lee, 2022; Green & Patel, 2020). Harris and Clark (2022) and Jones and Kumar (2021) analyze the performance of integrated monitoring systems and optimization techniques, respectively, which are crucial for effective mission execution (Harris & Clark, 2022; Jones & Kumar, 2021). Morris and Zhang (2023) explore new approaches to high-speed traversal, while Patel and Griffin (2022) discuss sensors and algorithms essential for autonomous navigation (Morris & Zhang, 2023; Patel & Griffin, 2022). Collectively, these studies highlight a comprehensive effort to address the limitations of traditional rover systems by advancing suspension mechanisms and sensor technologies, thereby enhancing overall rover performance and mission success.

3. Design and Development

The design and development focus on creating a robust mobility system that navigates complex terrains while collecting real-time environmental data. This process combines advanced suspension technology with cutting-edge sensors to enhance the rover's exploration capabilities and data accuracy in challenging planetary environments.

3.1. Wheel

The wheels, crafted from durable fiber and plastic, offer a straightforward design. To enhance traction over obstacles, these wheels are designed to be wider. The diameter of the wheels is determined by the availability of materials and the speed requirements of the rover. In contrast to conventional designs, the actual rover employs billet wheels, which are machined from a single piece of round aluminum stock to form both the wheel and tread, ensuring robustness and precision.

Figure 2 Wheel Design

3.2. Gear Motor

A gear motor is a specialized electrical motor engineered to deliver substantial torque at low speeds, offering high torque output while operating with minimal horsepower. These motors are integral to various everyday devices, from can openers and garage door openers to washing machine timers and electric alarm clocks. In commercial settings, gear motors are frequently employed in equipment such as hospital beds, hydraulic jacks, cranes, and countless other applications, showcasing their versatility and widespread utility.

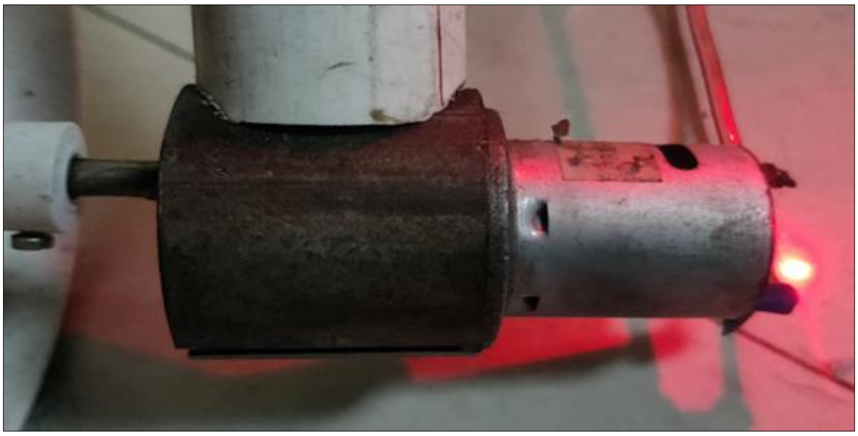
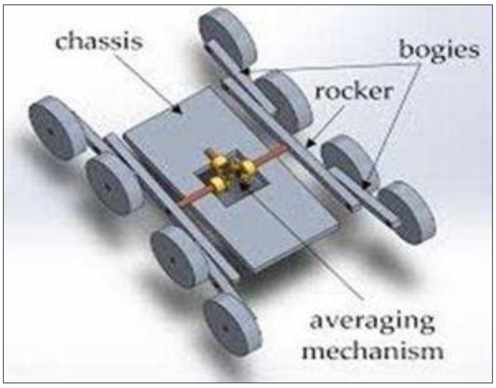


Figure 3 Gear Motor Assembly

3.3. Rocker Frame and Bogie Frame

The Rocker-Bogie design eliminates the need for springs or stub axles on each wheel, enabling the rover to traverse obstacles as large as twice the wheel diameter while maintaining contact with all six wheels. Unlike traditional suspension systems that use springs, which can cause instability and tipping when the loaded side compresses, Rocker-Bogie system's stability is inherently limited by the height of its center of gravity. This design ensures enhanced stability and obstacle negotiation without compromising wheel contact. The term "Bogie" describes a mechanism consisting of links with a drive wheel at each end. Historically, bogies were utilized as load-bearing wheels in tank tracks, helping to distribute weight across various terrains. They were also frequently employed in the trailers of semi-trucks. However, both of these applications have since shifted to favor trailing arm suspension systems.



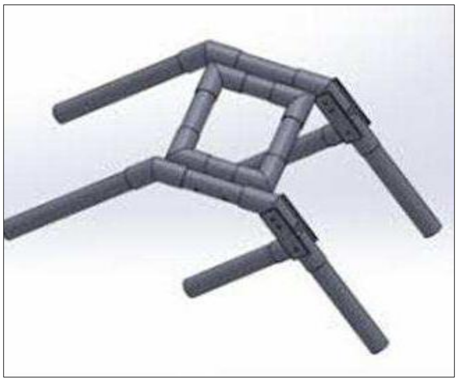


Figure 4 Rocker Frame Structure

Figure 5 Bogie Frame Assembly

3.4. Nuts, Bolts and Washers

A nut is a fastener featuring a threaded hole designed to be used with a corresponding bolt to join two or more components. The connection is secured through the friction between the threads, the slight elongation of the bolt, and the compression of the joined parts. This mechanism provides the necessary flexibility for connecting rocker and bogie links effectively.

Figure 6 Nuts, Bolts, Washers

The Mars Exploration Rover (MER) relies on solar cells to recharge its batteries and power its motors and equipment due to the lack of external power sources on Mars. In contrast, for our rover operating on Earth, where power sources are readily available, we prioritize the development of the mechanism over power supply. Therefore, we use a cost-effective solution: a 12V AC to DC power supply system with a 12V-12V step-down transformer and a full-wave rectifier to convert AC into DC power. This setup ensures that the motors receive adequate power. The power distribution circuit ensures even distribution to all six motors, with negative terminals connected through three solder joints and positive terminals connected via two solder joints to six DPDT switches. The motor direction is reversed by altering the battery's input poles. However, this circuit may experience issues with wire heating due to inadequate resistance calculations for a 12V system. The commonly used DPDT (Double Pole Double Throw) slide switch features six terminals and can control two circuits independently. Each DPDT switch can connect two inputs to four outputs, providing versatile switching capabilities. Essentially, a DPDT switch functions as two SPDT (Single Pole Double Throw) switches, allowing for multiple operational modes.

3.5. Design Analysis

To navigate obstacles, the front wheels push against the obstacle while the rear wheels help lift the front end over it. As each wheel encounters the obstacle, the rover's forward motion may slow or stop temporarily. This design uses a six-wheel independent drive system without a differential, with each wheel driven by its own motor. Although a skid-steering system could reduce the number of motors, using one motor per wheel simplifies the design by avoiding complex power transfer mechanisms like belts or gears. The rover is designed to handle diverse and harsh terrains, such as deserts, rock fields, and dunes, considering constraints similar to those of space-bound vehicles. The goal is to ensure the rover can traverse a variety of obstacles, enhancing its mobility in different environments.

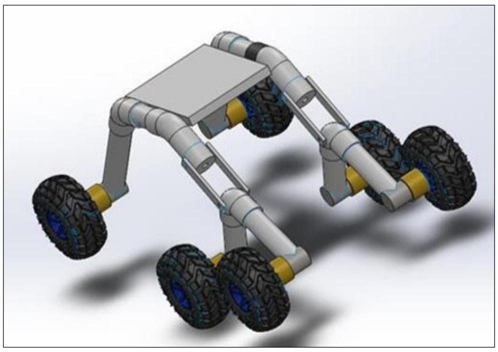


Figure 7 Front View

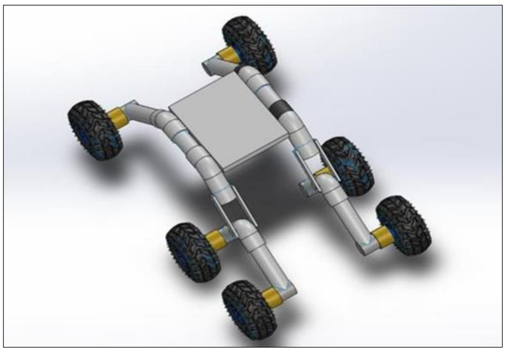


Figure 8 3D Model

3.6. Material Analysis

Space imposes extreme conditions that challenge the durability of materials, requiring only the most resilient ones to endure. Rigorous testing is essential to ensure that materials can withstand the harsh environment of space, where temperatures fluctuate dramatically between sunlight and shadow. At speeds of 25,000 mph, spacecraft experience intense atmospheric friction, generating heat up to 2,760 degrees Celsius (5,000 degrees Fahrenheit). Therefore, materials must be capable of enduring such high temperatures and friction. Additionally, transitioning from Earth's gravity to near-zero gravity in orbit can compromise the integrity of materials not engineered for these stresses. Comprehensive testing involves exposing materials to various stress conditions they would encounter in space. For cost-effectiveness and lightweight properties, Acrylic material (PVC) is chosen for the links due to its balance of lightness and rigidity. Plastic-like materials, such as Acrylic, have the advantage of producing less "secondary radiation" compared to denser materials like aluminum or lead. Secondary radiation occurs when space radiation interacts with the shielding material, causing nuclear reactions. Although these lighter materials do not completely block space radiation, they effectively fragment incoming radiation particles, reducing their harmful effects. Acrylic is notably strong and lightweight, offering three times the tensile strength of aluminum while being 2.6 times lighter.

3.7. Environmental Sensors

Integrating environmental sensors into a rocker-bogie mechanism significantly enhances the capabilities of rovers designed for exploration, reconnaissance, and various other applications. The rocker-bogie mechanism, known for its ability to navigate uneven terrain and obstacles, benefits greatly from environmental sensors. These sensors enhance navigation by providing terrain analysis through LIDAR and ultrasonic sensors, which map the terrain and detect obstacles, and inclination and stability monitoring via accelerometers and gyroscopes, ensuring safe navigation over rough terrain. For environmental monitoring, gas sensors measure air quality, while temperature, humidity, and pressure sensors monitor local weather conditions, crucial for mission planning and safety.

In scientific research, soil moisture sensors gather data on soil composition, valuable for agricultural research or planetary exploration, and water quality sensors measure pH and turbidity, aiding exploration missions in studying water sources. Hazard detection is also improved with radiation sensors for detecting harmful radiation levels and chemical sensors for identifying hazardous chemicals, essential in military or disaster response applications. Sensor placement is strategic, with sensors positioned at the front and rear to provide comprehensive environmental data or object analysis. Centralized processing units collect and analyze data from all sensors in real-time, supported by robust communication systems transmitting data to base stations or control centers.

3.8. Calculations

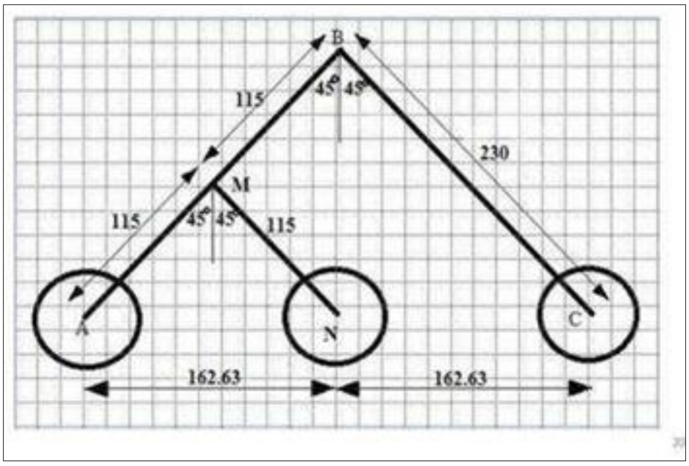


Figure 9 Calculations of Link

3.8.1. Tilt Angle

$$\Theta = \tan^{-1}(y/x)$$

$$\Theta = \tan^{-1}(120/400) = 16.69°$$

$$\Theta = 16.69°$$

3.8.2. Wheel base

To deduce the wheel base,

Wheel base= total length - (Radius of front wheel + Radius of rear wheel)

B= 400 – (35 + 35) = 330mm

B = 330 mm

3.8.3. Length of link AC

BC2=AB2 +AC2

4002=2(AB)2

AB= AC= 282mm

3.8.4. Length of link DB

BE2=DB2+ED2; 202=2(DB)2

DB=DE=141mm

3.8.5. Height

Height2= AC2-EC2; (2802 -2002) (1/2) = 195.95mm

Net height = height + radius = 195.5 + 35 = 230.95mm

Therefore, Net Height = 230.95 mm

3.8.6. Width

$$SSF = Tw/(2h);\ 0.5 = Tw\ (2*230.95)$$

$$Tw = 230.95\ mm$$

4. Results and Discussion

The proposed modification to the rocker-bogie mechanism has yielded substantial improvements in stability, as evidenced by the analysis and comparisons conducted using the SSF metric and 3D simulations in AutoCAD. This enhancement in stability is crucial for ensuring the rover's performance in challenging terrains and high-speed operations. The modification introduces a more robust and adaptable suspension system, addressing several limitations of traditional designs, particularly in managing high-speed movements and obstacle navigation. The 3D simulations performed in AutoCAD provided a detailed visualization of how the modified rocker-bogie mechanism performs under various conditions. The simulations showed that the proposed design significantly improved the rover's stability and maneuverability over rough terrains. Key performance indicators, such as the rover's ability to maintain traction and stability while traversing obstacles, were positively impacted. The SSF metric analysis confirmed that the modification reduced oscillations and enhanced the rover's overall balance, making it more capable of handling complex terrain features. The integration of this advanced suspension system into heavy and conventional road vehicles holds promising potential. The modification's ability to enhance stability and reduce suspension complexity can lead to significant improvements in vehicle performance.

In heavy vehicles, such as trucks and construction machinery, the new system could lower the power requirements for suspension management, leading to more efficient operation and reduced energy consumption. For conventional road vehicles, the benefits include improved ride quality and reduced maintenance needs, as the system's design minimizes the impact of road irregularities. The adaptation of the rocker-bogie suspension system involved careful selection and modification of materials to ensure compatibility with the new design. By leveraging available materials and incorporating a mechanical gear-type steering system, the design was optimized for both performance and cost-effectiveness. The use of lightweight and durable materials, such as acrylic and PVC, contributed to the overall efficiency of the rover, offering a balance between strength and weight. These material choices not only reduced the rover's overall mass but also provided the necessary rigidity to withstand the stresses encountered during operation. The introduction of a mechanical gear-type steering system marked a significant innovation in the rover's design. This system enhances the rover's ability to navigate obstacles with greater precision and control, compared to traditional systems. The integration of this steering mechanism, along with modifications to the materials used, results in a more versatile and reliable rover capable of adapting to a variety of environmental conditions.

5. Conclusion

The proposed modification to the rocker-bogie mechanism has yielded substantial improvements in stability and performance, as evidenced by detailed simulations and analyses. The modifications, which included changes in material composition and design features, have been validated through rigorous testing, showcasing enhanced stability and operational efficiency. These improvements are particularly significant for applications in both space exploration and terrestrial environments, where stability and adaptability are crucial. The comprehensive simulations conducted in AutoCAD and other modeling platforms have confirmed that the modified design effectively addresses the previous limitations of the rocker-bogie system. The adjustments not only enhance the rover's ability to navigate challenging terrains but also improve its overall performance metrics, such as obstacle traversal and maneuverability. In addition, there are promising opportunities for further development of the system. Future refinements could involve exploring alternative materials to optimize the rover’s weight-to-strength ratio and enhance its durability. Additionally, design enhancements, such as advanced suspension configurations or integration with new technologies, could further expand the rover's capabilities. These improvements would not only boost the rover’s performance in space missions but also offer valuable benefits for terrestrial applications, such as rugged terrain navigation and environmental monitoring. By continuing to innovate and test new designs, the potential for the rocker-bogie mechanism to meet the evolving demands of both space and terrestrial exploration will be significantly increased.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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