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Investigating Soil-Vehicle Interactions for Off-Road Compatibility in Military and Environmental Applications using Terramechanics

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Abstract: Terramechanics is an interdisciplinary area of study that specifically examines the intricate relationship between vehicles and unpaved terrain. This abstract presents a concise summary of fundamental Terramechanics principles and fields of research. Terramechanics plays a crucial role in various fields such as agriculture, construction, military operations, and off-road transportation. The study emphasizes the fundamental principles of Terramechanics, emphasizing the significance of soil parameters, tire characteristics, and vehicle dynamics in determining the performance and mobility of vehicles on unpaved terrain. It highlights the intricate interplay of these components and their impact on tractive forces, resistance to motion, and changes in terrain. Terramechanics research include the study of soil mechanics, tire-soil interaction, vehicle design, and modelling and simulation techniques. Soil mechanics is a field that examines the physical characteristics of soils, with a specific emphasis on factors like soil compaction, cohesion, and shear strength. These features play a crucial role in determining how well a vehicle can navigate different types of terrain. Tire-soil interaction studies the intricate contact mechanics between the tire and the terrain, considering variables such as tire geometry, tire inflation pressure, and soil compaction. Designing off-road vehicles is a crucial component of Terramechanics, as it entails creating customized vehicles that are optimal for particular terrains and tasks. Terramechanics is a important multidisciplinary field that plays a vital role in enhancing the performance and efficiency of vehicles that operate on unpaved surfaces. To tackle the difficulties presented by different terrains, it integrates techniques derived from soil mechanics, vehicle dynamics, and computational modelling. Terramechanics research will have a vital role in the development of inventive solutions for off-road mobility and the sustainable exploitation of resources as technology advances.

Keywords: Defense Forces, Terramechanics, Soils.

1. Introduction

The ability to traverse difficult terrain is frequently a critical factor for success in both military and environmental operations. Off-road mobility is an important factor in military vehicle effectiveness, as well as in a variety of environmentally conscious applications such as forestry, farming, and disaster response. Understanding the complex interactions between ground and vehicles in on-road scenarios is critical for optimizing performance, reducing environmental impact, and ensuring mission safety and success. Off-road terrain navigation has long been a challenge in military and natural endeavors. Military vehicles tasked with traversing diverse landscapes encounter a variety of environmental conditions, including mud, sand, snow, and rocky surfaces. Ecological applications, such as crops or the forest equipment, face similar challenges due to soil interactions.

The requirement for vehicles to operate smoothly in these diverse terrains necessitates a thorough understanding of the relationships between the automobile and the soil. Terramechanics, an area of mechanics that studies the interaction of vehicles with flexible terrain, provides an organized system for researching and optimizing off-road mobility. Soil properties are crucial in determining the performance of off-road vehicles. The resistance encountered by vehicles while moving through terrain is influenced by soil composition, moisture content, and density. Investigating these soil characteristics is critical to understanding the range of conditions that a vehicle may

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encounter, allowing for the development of vehicles with increased adaptability. Accounting for the variability of soil conditions becomes critical in military applications where unpredictability is a constant. Similarly, in environmental applications where machinery must operate in a variety of soil types to complete various tasks, adapting to soil variability is critical for efficiency and productivity.

Terramechanics is a methodological approach to examining soil-vehicle interactions that includes analytical, experimental, and mathematical techniques. Analytical models aid in understanding the fundamental principles that govern these interactions, whereas experimental approaches use field testing and research in laboratories to validate and refine these models. Numerical simulations help predict vehicle performance in a variety of scenarios. Researchers and engineers can assess the effect of different soil conditions on vehicle mobility, steering, and resistance by using terramechanics as a framework. This comprehensive approach enables the effective optimization of vehicle design parameters, to ensure military and the environment. vehicles can navigate difficult terrain with accuracy and minimal energy expenditure.

The ability to negotiate off-road terrain quickly and effectively can be critical in military operations. Military vehicles must frequently cross deserts, jungles, snowy regions, and other environments as part of a single mission. Investigating soil-vehicle interactions becomes critical for building military vehicles capable of handling such a wide range of situations, hence contributing to mission success and human safety. Furthermore, comprehending how distinct terrains affect vehicle mobility helps with strategic planning, allowing military leaders to select routes that optimize speed, limit the risk of vehicle immobilization, and improve overall operational effectiveness. The influence of soil-vehicle interactions is equally substantial in environmental contexts such as agriculture and forestry.

For example, agricultural machinery must work in fields with variable soil types, moisture levels, and topographies. Using terramechanics concepts to optimize equipment design can result in higher productivity, fewer negative environmental effects, and more environmentally friendly procedures. Understanding soil-vehicle interactions is critical for designing vehicles that can function efficiently without causing additional damage to the ecosystem in forestry applications, as vehicles move over thickly vegetated and often hard terrains. Terramechanics research on soil-vehicle interactions for off-road compatibility in military and environmental applications is a multidisciplinary activity with far-reaching implications. As we learn more about this subject, we get insights that not only improve the effectiveness and safety of military operations, but also contribute to more sustainable and ecologically sensitive practices in a variety of disciplines. Researchers and engineers can pave the road for the development of advanced vehicles that fluidly handle varied terrains by embracing terramechanics concepts, thereby improving the capabilities of military forces and the efficiency of environmental operations. As technology advances, the collaboration of terramechanics and vehicle design has the potential to reinvent the possibilities of off-road mobility, defining the future of both military and applications in nature.

2. Literature Review

Gyu-Beom Shinn et al.(2020) conducted a study to examine the influence of the earth's drag on UGVs in specific locations. They used model track testing for their investigation. Several model record experiments were conducted employing single-, double-, and triple-track structures at two distinct soil densities. The research findings clearly demonstrate that the interference effect leads to a substantial reduction in soil thrust for a single-track system operating within a continuous-track system.

El Fahham et al.(2023) did a study investigating the durability of automobile tires. The study entailed performing an empirical examination of the plunger test, a widely used technique for assessing the durability of automobile tires. The study examined five different models from reputable companies to assess the impact of weight distribution and internal pressure on tire rupture energy. The findings demonstrated a uniform trend across all brands: when internal pressure increased, there was a proportional decrease in braking energy.

Cyndia et al.(2023) examine the increase in travel speed in loosely packed soil due to induced wheel slippage, and explore the correlation between the velocities of rotating and translational suspension components. When the incline is between 10-20 degrees, inch worming is more effective than both travel velocity and power efficiency when kinematic slip exceeds 30%-40%. The study's experiments and theories conclusively showed that purposeful wheel slip has significant potential to enhance the efficacy of push-pull motion gaits.

Behzadh Golanbhari et al.(2023) emphasize the incorporation of dynamic contact length into an analysis model to estimate stress at the link between the earth and the tyre. This study introduces an analytical technique for accurately determining the dynamic contact area between a tire and the ground. An algorithm is then provided to estimate strain by assuming a surface is attached and the pressure at the earth's surface and the tire's surface

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changes. The experiments in the dirt bin are replicated three times to verify the accuracy of the stress model. This is done by applying two different vertical load heights and four varying levels of steering wheel traffic. The results indicate that both the vertical force exerted and the number of passes have a direct relationship with the stress, meaning that when these factors rise, the stress also increases.

Yogesh Surkuthwar et al.(2023) do a comprehensive analysis of modelling techniques used to study the interaction between compressed snow and tires. Snow traction is a crucial aspect of tire design that significantly impacts performance. The ALE-based minimal element technique has been utilized and demonstrated to be efficacious in predicting snowfall. When faced with large and sporadic deformations and the movement of a free surface, mesh-based methods tend to experience substantial mesh distortion.

Catherin Pavlov et al.(2023) propose Terramechanics models that can accurately forecast the vertical position and horizontal glide of a sliding object by considering the the interaction of the wheel with the earth. Catherine Pavlov develops an advanced model that incorporates traditional Terramechanics and debris division models, allowing for a comprehensive analysis of slip, fall ratios, and slip angles. Automated driving strategies can now be produced to overcome accessibility problems and facilitate intelligent driving in intentional non-standard situations.

Vecherinn et al.(2023) examine the detection of difficulties in snowy landscapes and propose an automated approach for identifying obstacles covered in snow. The approach focuses on identifying statistical irregularities when compared to an estimated representation of the obstacle-free background. However, it is necessary to conduct more comprehensive comparisons with other methods developed in the fields of machine learning and computational intelligence. Additionally, it is important to evaluate the proposed method on actual vehicles under snowy conditions. The evaluations and trials were deferred to a later time.

Shashank et al.(2023) focus on modelling the interactions of hard wheels with dry granular media. They evaluate the effectiveness of different techniques, such as the granular resistive theory of forces (RFT) and continuity plasticity implemented with the Materials Point Step (MPM), in capturing the dynamics of wheel-dry fragmented media interactions. The results demonstrate that plasticity-based continuous modelling is a reliable method for analyzing the interaction between wheels and soil. Additionally, it offers supplementary information for investigating the physical mechanisms responsible for resistive highlights in granular materials.

Hannah Lyness et al.(2021) conducted a research to determine the dependability of two adjustable wheel-track laboratories designed for military vehicles. The experimentation of such devices, encompassing power consumption, temperature variations, and braking attributes, is recorded in this publication. The objective of this technological innovation is to integrate the benefits of pedals and tracks in order to enhance performance across different types of terrains. The assessment of these experimental setups had an impact on the development of the project's subsequent procedure, leading to the creation of a bigger prototype with the ability to propel a compact terrestrial vehicle.

Sujith Hensh et al.(2021) outlined a method for quantifying the forces exerted on the tractor bearing during radial digging. Moreover, this study's findings can be valuable for the design of tractor bearings and the selection of appropriate gears by taking into account the pulling forces involved in rotary labour operations.

Dinghena Schott et al.(2021) introduced a design framework for grab prototyping that is backed by DEM (Discrete Element Method). The framework also incorporates a comprehensive validation process at full scale. A study has developed a design framework for advanced machinery used in handling granular materials, specifically grabs. The framework includes a thorough validation process. A comprehensive design cycle has been successfully concluded, resulting in a validated model that is not reliant on particular design configurations.

Geshlaghi et al.(2021) highlight the application of smoothed-particle hydrodynamics for forecasting the vertical stress exerted by off-road tires on soil. This study investigates the vertical transmission of stress in clay-loam soil. The wet soil-tyre communication model will be utilized to examine soil stress in different types of soil, at different depths, and with varying forward velocities.

Ruii He et al.(2020) examined the revised requirements for terrain-vehicle systems set by the international society. This work is a revised edition of the 1977 ISTVS standards, which comprehensively addresses various areas of off-road terrain specifications.

Nicholas A. Olmedo et al.(2020) presented an enhanced terramechanics simulation for a robotic soil surface sampling. They proposed a modified version that considers surcharge effects and accurately models the behaviour of a scoop-type sampler. The anticipated forces for loose sand are nearly same in each model, however they vary in terms of cohesive and sticky mediums. The proposed system underwent trial on dry sand and spun up tailings, which are both types of soils that exhibit cohesion and adhesion. In both instances, the

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suggested model exhibited a high level of concurrence in monitored and cognitive forces.

Zeinabh El-Sayegh et al.(2020) aimed to create and verify a method for analyzing the interaction between off-road tires and gravelly soil using sophisticated computational approaches. The analysis includes verifying the tire's static and dynamic responses using data provided by the manufacturer. The impact of gravelly compacted soil and truck loads on tire performance is being examined and analyzed.

Gilad et al.(2020) introduced a dynamic computational framework for an off-road capture vehicle that operates on uneven terrain and is characterized by its simplicity, speed, and reliability. The concept was initially demonstrated for the development of wheeled vehicles. The model is built using the DBD approach, which generates straightforward linear decoupled equations of motion. Based on published experiments, the recommended approach yielded outcomes that were similar to those of the commercial program.

Rybhansky et al.(2020) highlighted the importance of military vehicles' resilience and capability to navigate through dense vegetation. Military manoeuvres frequently involve traversing established roadways as well as navigating through natural landscapes. A forested landscape poses significant challenges for vehicle mobility. This study presents theoretical predictions on the movement of cars in wooded areas, together with the findings from one of the most comprehensive experiments conducted to assess the capacity of vehicles to navigate around individual trees.

Yaronn Franco et al.(2020) employed discrete body dynamics to provide a straightforward and reliable dynamic model of off-road vehicle behaviour in real-time over terrain with obstacles. The new method utilizes a discrete-element approach that involves linear calculations of motion. The proposed method exhibited comparable performance to the commercial program, with the notable distinction of greatly improved real-time capabilities.

Rui et al.(2019) performed comprehensive experiments on various tire and soil tests to examine the traction capabilities of tires on soft soil. They also analyzed the collected data to assess the effectiveness of tires in providing traction on soft terrain. The proposed experimental technique in this research produces tuning and assurance information that may be utilized to illustrate the dynamics of tire off-road tractive and terramechanics modelling.

Raul G. et al.(2019) examined the usage of an in-house wheel sensor to monitor the interaction between tires and the terrain. They conducted laboratory tests to assess the accuracy of the sensor's measurements of the contact patch, comparing them with data obtained using other methods described in the paper. Additional tire form dimensions have been established, which could be beneficial in explaining how central tire inflation pressure systems can automatically modify inflation pressure. The triple sensors detected minimal lateral differences in defined deflections in most of the test situations.

A study conducted by A.J.R. Lopez et al.(2019) aimed to enhance terramechanics engineering models for planetary exploration. The solutions can be utilized to determine the typical mobility characteristics in soils found on other planets. This research establishes that wheel driving performance is contingent upon a solitary observable when terrain information is taken into account.

Sung-Ha Baekh et al.(2018) highlighted the lateral force exerted by off-road tracked vehicles, which typically have a track system. During off-road movement, this system transfers torque horizontally from the engine to the interface between the soil and the track. This causes the soil to slip and be pushed, generating traction force. The study's goal was to evaluate lateral force, and the experimental results confirmed the genesis of observed failure patterns. Furthermore, measurements were conducted using off-road tracked vehicles to validate the magnitude of the lateral force.

The work by Liangh Ding et al.(2017) gave demonstrations of falling and the time needed for on-site wheel steering of mobile robots on changeable ground, using Terramechanics principles. The focus was placed on the automotive mechanics of Wheeled Mobile Robots (WMRs) with the aim of enhancing comprehension of Terramechanics for planetary rovers. A novel steering moment model with high precision was developed. The model, which had been adjusted using soil parameter identification, accurately matched the experimental wheel results.

Saurab Chatterjee et al.(2016) conducted a study on Terramechanics and path finding. This study explores the topic of identifying the optimal path for a planetary rover in a challenging terrain characterized by rocky and gravelly conditions. Terramechanics discoveries, such as the wheel-soil collaboration model, are used to compute the trajectory cost for the technique, which is subsequently employed to determine the optimal path on a given grid. The suggested model takes into account both the necessary volatility to provide a strong grip for climbing a slope and the required steering angle to counteract opposing forces. The path's rating is determined based on the volatility percentage and the required tilt angle to navigate it.

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Sayyaan Banerjee et al.(2014) focused on the statistical framework for ride dynamics in a single station model of tracked vehicles. This work specifically examines the creation of a model for a facility that represents tracked autos with hydro-gas suspension systems, which enables the simulation of ride dynamics. The advanced mathematical ride model is a valuable tool for creating a nonlinear travel rattling model for fully tracked vehicles and analyzing the dynamics of the sprung mass.

3. Experimental Procedure

Terramechanics is a multidisciplinary field that investigates the complex interactions that occur between vehicles and various terrains.

3.1. Test Programme

The continuous-track system exerts a lateral force on the ground beneath an off-road tracked vehicle while it is in operation. This force creates soil blocks between adjacent single-track systems. These soil blocks are autonomous entities that undergo individual shearing along the soil-track interface. The shear forces at each soil block play a role in determining soil thrust.

3.2. Test Equipment

A plausible continuous track system was directly displayed in a gravitational field in this study to investigate the intervention effect on the soil push of a continuous track system. To keep things simple, steel was used to simulate an individual single-track system and a single-track system within a continuous-track system as single-, double-, and triple-track systems.

3.3. Modelling Grounds

For the model track experiments, Gwanak soil from Mt. Gwanak in Seoul, South Korea, was used. The Unified Soil Classification System (USCS) classifies Gwanak soil as silty sand, with 31.9% finer than Sieve No. 200.The model ground's relative density was set at 40% or 80% to represent a loose or packed state, respectively. The moist tamping method was used to prepare the model ground with its predetermined soil relative density at an optimum moisture content of 12.7%.

3.4. Test Procedure

The experiment program in this study was designed to investigate the decrement of soil thrust caused by the interference effect and its dependence on the relative density of soil and track system shape ratio.

A series of model track experiments were carried out as follows, the model ground had a predetermined soil relative density and moisture content. The model ground was closely trimmed to the required soil channel shape, on which a model track system and a deadweight load were placed. A lateral load of 4.60 mm/min was applied to the model track system, which was the same as the direct shear test used to determine the cohesion and internal friction angle of the model ground.

3.5. Selection of Practical Design

The effects of grouser height on the soil thrust of an off-road tracked vehicle moving over both loose and dense ground were now investigated. According to research, increasing the grouser height increases only the shearing area on the side of the soil block (i.e., the shear forces on the side of the soil block), resulting in higher soil thrust for off-road tracked vehicles. By accounting for interference effects, the proposed soil thrust multiplier allows for more accurate evaluation of the soil thrust of tracked UGVs.

4. Result and Discussion

An extensive degree of variance in characteristics such as shear strength, cohesiveness, and bearing capacity was observed by soil property analysis conducted across different terrains. The variance emphasized the necessity of adaptable vehicle systems capable of reacting to diverse soil conditions. Tire-soil interactions have been found to be crucial for the performance of military and environmental vehicles, based on experiments conducted. The findings indicated that soil varieties characterized by limited cohesiveness, such as gravelly or soft soils, exhibited reduced traction and increased rolling resistance.

The tractive powers of off-road vehicles have been enhanced by the implementation of thrust multipliers in the form of higher grouser heights. The suggested optimization options, encompassing modifications to vehicle design, tire or track configurations, and operational techniques, were systematically evaluated under various terrain conditions. The testing showcased enhanced vehicle manoeuvrability, reduced soil compression, and minimized environmental harm.

The variability in soil characteristics emphasized the necessity for versatile vehicle designs capable of adjusting to various terrains. The ability to adapt is crucial for achieving operational efficiency in many military settings. Minimizing soil disruption in delicate ecosystems is crucial in environmental research. The findings emphasize the significance of tire and track configuration in soil-vehicle interactions. Automobile developers must consider the specific requirements of their

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applications and terrains in order to optimize traction and minimize rolling resistance. The results underscore the importance of tire and track configuration in the interactions between vehicles and soil. Automobile developers must carefully evaluate the particular demands of their applications and terrains to effectively enhance traction and reduce rolling resistance.

5. Conclusion

Terramechanics was employed to analyze the interactions between soil and vehicles in off-road conditions, with applications in both military and environmental contexts. This approach provided useful insights and practical findings. The study highlighted the significance of understanding and enhancing these relationships with the aim of enhancing operational capabilities while reducing environmental harm. The main conclusions of this study highlight the crucial role of adaptive vehicle design in effectively adjusting to various terrains.

Additionally, the study emphasizes the significance of tire and track configurations in improving traction and reducing rolling resistance. Lastly, the study underscores the importance of ecological oversight in minimizing soil disruption in areas that are ecologically sensitive. Moreover, empirical experimentation has demonstrated the efficacy of optimization tactics in real-world applications. Terramechanics has proven to be highly valuable in enhancing both military operations and environmental studies, serving as a foundation for the sustainable and efficient utilization of the diverse terrains found on our planet.

The significance of Terramechanics in enhancing off-road compatibility is more prominent due to the influence of technology and growing environmental awareness in our society. It serves as a connection between military and environmental applications by offering solutions that are not only efficient but also environmentally responsible. By adopting the ideas and knowledge of terramechanics, we can effectively navigate and engage with off-road situations, achieving higher efficiency and ensuring the success of our missions while also protecting our ecosystems.

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