Mathematical Model and Kinematic Analysis of Rocker-Bogie Suspension Design for UGV Applications

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***Abstract* – Unmanned Ground Vehicles (UGVs) deployed in complex, unstructured environments demand suspension systems that ensure robust wheel–terrain contact, stability, and adaptability. The Rocker-Bogie mechanism originally developed for planetary rovers has emerged as an attractive solution due to its passive adaptability, kinematic redundancy, and energy efficiency. This paper presents a new mathematical model and kinematic analysis of the Rocker-Bogie suspension design as applied to UGVs. We derive the forward kinematics, establish differential relationships via the Jacobian matrix, and detail an iterative approach for inverse kinematics. Furthermore, we develop a Lagrangian dynamic formulation to capture the transient behavior and shock absorption characteristics of the suspension. Simulation studies illustrate the model's validity over a range of terrain profiles, and sensitivity analyses highlight the influence of key design parameters. Finally, we discuss adaptive control strategies and avenues for future research, aiming to optimize Rocker-Bogie UGV performance in challenging environments.**

Keywords— Unmanned Ground Vehicle-UGV, Rocker-Bogie suspension design, Kinematic design, Mathematical model

I. INTRODUCTION

The evolution of unmanned ground vehicles (UGVs) over recent decades has been driven by the need for reliable mobility across diverse and often harsh terrains. In applications ranging from military reconnaissance to search-and-rescue operations and hazardous material handling, the capability to traverse irregular and unpredictable surfaces is paramount. Conventional suspension systems, such as rigid axles or independent suspensions have demonstrated limitations in maintaining continuous wheel terrain contact when confronted with obstacles, slopes, and rough ground. In contrast, the Rocker-Bogie suspension system, which was initially developed for extraterrestrial rovers, exhibits superior performance due to its unique passive adaptability and kinematic redundancy.

The Rocker-Bogie mechanism achieves terrain conformity by employing two interconnected subassemblies (the rocker and the bogie) that work in tandem to distribute the vehicle's load and maintain at least one wheel per side in contact with the ground at all times. For UGVs, the adaptation of the Rocker-Bogie design involves modifications in geometry, material selection, and control strategies to meet terrestrial operational demands. In particular, the integration of a mathematical model that encapsulates the system's kinematics and dynamics is essential for understanding its behavior and optimizing design parameters.

The Rocker-Bogie suspension system is composed of two primary assemblies: the rocker and the bogie. The rocker serves as a larger, primary beam that attaches directly to the rover body, while the bogie is a secondary assembly pivoted to the rocker. Each of these assemblies is connected to wheels via independent joints that allow for angular movement relative to the body of the rover. The configuration can be visualized as a multi-link chain where the interaction of the various joints governs the overall kinematics of the system.

Key design principles include:

Passive Adaptation: The system is designed to automatically adjust to terrain irregularities without the need for active control inputs.

Wheel-Terrain Conformity: Maintaining continuous wheel contact with the surface is critical for traction. This is achieved through careful balancing of the degrees of freedom and pivot locations.

Load Distribution: The design minimizes the effect of uneven loading by distributing forces across the multiple joints and links.

The literature has extensively discussed the benefits and limitations of the Rocker-Bogie design. Researchers have modeled its behavior under various conditions, emphasizing its robustness in dynamic environments [1]. Recent studies have further elaborated on the dynamic response of the mechanism, integrating finite element analysis (FEA) with kinematic simulations to predict behavior under stress [2].

II. RELATED WORKS

Existing literature on Rocker-Bogie systems includes:

Kinematic Modeling: Several works have derived the geometric relationships between joint angles, link lengths, and wheel positions, primarily in the context of planetary rovers. These models have been adapted for UGVs by incorporating terrestrial load distributions and terrain profiles.

Dynamic Analysis: Researchers have employed Lagrangian mechanics and multibody dynamics to analyze energy transmission, shock absorption, and transient responses in Rocker-Bogie suspensions.

Control Strategies: The inherent kinematic redundancy of the system has been leveraged to develop adaptive and robust control schemes that optimize for stability, energy consumption, and terrain conformity.

Experimental Validation: Field tests and laboratory experiments with prototype vehicles have confirmed many of the theoretical predictions, although challenges remain in bridging the gap between idealized models and real-world behavior.

Our work seeks to build on these contributions by presenting a complete mathematical model that integrates both kinematic and dynamic aspects, with an emphasis on its application to UGVs.

III. Mathematical model and Kinematic analysis

In a typical Rocker-Bogie UGV, the suspension is arranged symmetrically about the longitudinal axis. Each side of the vehicle consists of two main articulated subassemblies:

Rocker Assembly: This assembly is connected directly to the UGV chassis via a primary pivot. It is responsible for supporting the bulk of the vehicle's mass and adapting to pitch changes.

Bogie Assembly: Connected to the rocker by a secondary hinge, the bogie introduces additional degrees of freedom. In most designs, two wheels are attached to the rocker while a third wheel is mounted on the bogie. This configuration ensures redundant contact with the terrain, even when one subassembly is significantly perturbed.

A simplified schematic (see Figure 1) illustrates the key components of the Rocker-Bogie suspension system. In our model, the suspension is abstracted as a multi-link mechanism, where each link is considered a rigid body with known geometric parameters and each joint provides one degree of rotational freedom.

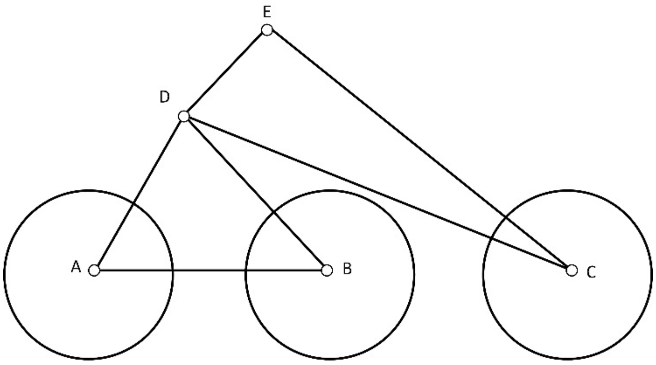

Fig.1 Rocker-Bogie suspension system

To facilitate a tractable mathematical analysis, we adopt the following assumptions:

Rigid Body Approximation: All links are assumed to be perfectly rigid. Elastic deformations are neglected.

Ideal Revolute Joints: Joints are modeled as frictionless revolute hinges with no backlash.

Planar Motion (Initial Analysis): The primary analysis is conducted in the sagittal (vertical) plane. An extension to three-dimensional (spatial) dynamics is discussed in later sections.

Continuous Wheel Contact: It is assumed that wheels maintain contact with the terrain at all times and that slip is negligible.

Symmetric Mass Distribution: The UGV is assumed to have a symmetric mass distribution with respect to its longitudinal axis, which simplifies the dynamics.

Small Angle Approximations: In portions of the analysis, small angle approximations are used to linearize certain expressions. However, the full nonlinear model is derived for completeness.

These assumptions allow us to develop clear and concise analytical expressions that capture the essential behavior of the Rocker-Bogie system.

We begin by establishing a global inertial coordinate system **{X,Y,Z}** with **Z** representing the vertical direction. For the initial planar analysis, we confine our discussion to the **XZ**plane. Each link of the suspension is associated with a local coordinate frame. The transformation from one link's frame to the next is expressed using homogeneous transformation matrices.

For a given link ***i*** with length ***Li*** and joint angle ***θi***, the transformation matrix ***Ti*** is defined as:

$$T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & L_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i & L_i\sin\theta_i \\ 0 & 0 & 1 \end{bmatrix}. \tag{1}$$

The overall transformation from the base (attached to the UGV chassis) to the end of link nn is then given by the product

$$T = T_1T_2\cdots T_n = \prod_{i=1}^{n} T_i. \tag{2}$$

The configuration of the mechanism is fully described by the vector of joint angles

$$q = \{\theta 1, \theta 2, \dots, \theta n\}. \tag{3}$$

The forward kinematics problem requires determining the position **p** of the wheel contact point in terms of the joint angles and link lengths. In homogeneous coordinates, the position is given by

$$\mathbf{p} = T\begin{bmatrix}0\\0\\1\end{bmatrix} = \begin{bmatrix}x\\z\\1\end{bmatrix}. \tag{4}$$

Expanding the above expression, the **x** and **z** coordinates are:

$$x(q) = \sum_{i=1}^{n} L_i\cos\left(\sum_{j=1}^{i}\theta_j\right), \tag{5}$$

$$z(q) = \sum_{i=1}^{n} L_i\sin\left(\sum_{j=1}^{i}\theta_j\right). \tag{6}$$

For the Rocker-Bogie UGV, we conceptually separate the kinematic chain into two segments - one corresponding to the rocker assembly and the other to the bogie assembly. Let qR denote the set of joint angles in the rocker and qB the set in the bogie. Then the position of a wheel contact point is expressed as

$$\mathbf{p}_{wheel} = \mathbf{p}_0 + \mathbf{p}_R(q_R) + \mathbf{p}_B(q_B), \tag{7}$$

where $\mathbf{p}_0$ is the location at which the suspension attaches to the vehicle chassis. This formulation permits the independent design of rocker and bogie geometries so that wheel trajectories closely follow the terrain surface.

The sensitivity of the end-effector's position to variations in the joint angles is captured by the Jacobian matrix $J(q)$. The Jacobian relates the joint velocity vector $\mathbf{q}^{\cdot}$ to the velocity $\mathbf{p}^{\cdot}$ of the wheel contact point:

$$\dot{\mathbf{p}} = J(q)\,\dot{q}. \tag{8}$$

For the **k**-th joint, the partial derivative of the end-effector position with respect to $\boldsymbol{\theta}_k$ is given by

$$J_k(q) = \frac{\partial \mathbf{p}}{\partial \theta_k}. \tag{9}$$

Differentiating the expressions for $x(q)$ and $z(q)$ yields

$$\frac{\partial x}{\partial \theta_k} = -\sum_{i=k}^{n} L_i \sin\left(\sum_{j=1}^{i} \theta_j\right), \tag{10}$$

$$\frac{\partial z}{\partial \theta_k} = \sum_{i=k}^{n} L_i \cos\left(\sum_{j=1}^{i} \theta_j\right). \tag{11}$$

Thus, the k-th column of the Jacobian is

$$J_k(q) = \begin{bmatrix} -\sum_{i=k}^{n} L_i \sin\left(\sum_{j=1}^{i} \theta_j\right) \\ \sum_{i=k}^{n} L_i \cos\left(\sum_{j=1}^{i} \theta_j\right) \end{bmatrix}. \tag{12}$$

Stacking the columns for k=1,2,…,n results in the full Jacobian matrix

$$J(q) = \begin{bmatrix} J_1(q) & J_2(q) & \cdots & J_n(q) \end{bmatrix}. \tag{13}$$

The Jacobian not only provides insight into how joint velocities affect wheel position but also plays a critical role in solving the inverse kinematics problem.

The inverse kinematics problem involves determining the set of joint angles q that will produce a desired wheel contact position p_d:

$$\boldsymbol{p}(q) = \boldsymbol{p}_d \tag{14}$$

Because the kinematic equations are nonlinear and the system may be redundant, iterative numerical methods are typically employed to solve for q. One common approach is the damped least-squares (DLS) method. The update rule for the joint angles at iteration k is

$$q^{(k+1)} = q^{(k)} - \left[J(q^{(k)})^T J(q^{(k)}) + \lambda I\right]^{-1} J(q^{(k)})^T \left(\mathbf{p}(q^{(k)}) - \mathbf{p}_d\right), \tag{15}$$

$\boldsymbol{\lambda}$ is a small damping parameter that ensures numerical stability (especially near singular configurations),

I is the identity matrix,

$\mathbf{p}(\mathbf{q}^{(k)})$ is the current estimate of the wheel contact point.

Convergence is monitored by checking whether the norm ‖Δq‖ falls below a predetermined threshold. In practice, the inherent kinematic redundancy in the Rocker-Bogie system allows for multiple solutions; additional criteria such as minimizing joint motion or avoiding extreme joint angles can be incorporated into the optimization process.

IV. *Dynamic Modeling Using Lagrangian Mechanics*

While the kinematic analysis determines the geometric relationships between joint angles and wheel positions, dynamic modeling is essential for understanding the suspension's response to external disturbances, shocks, and varying terrain conditions. The dynamic behavior is influenced by inertial forces, gravitational loads, and energy dissipation through damping elements. A dynamic model is also necessary for the development of control strategies aimed at mitigating transient disturbances.

The Lagrangian method provides a systematic way to derive the equations of motion for a mechanical system. The Lagrangian $\mathcal{L}$ is defined as the difference between the kinetic energy T and the potential energy V:

$$\mathcal{L}(q,\dot{q}) = T(q,\dot{q}) - V(q). \tag{16}$$

For the Rocker-Bogie system, the generalized coordinates are the joint angles q and their time derivatives $\dot{q}$.

The kinetic energy of the system is the sum of the kinetic energies of each individual link. For link i with mass m_i, moment of inertia I_i about its center of mass, and center-of-mass velocity $\dot{p}_i$, the kinetic energy is given by

$$T_i = \frac{1}{2} m_i \|\dot{\mathbf{p}}_i\|^2 + \frac{1}{2} I_i \dot{\theta}_i^2. \tag{17}$$

Expressing $\dot{p}_i$ in terms of the joint velocities $\dot{q}$ via appropriate Jacobian matrices allows us to write the total kinetic energy as

$$T(q,\dot{q}) = \frac{1}{2}\dot{q}^T M(q)\dot{q}, \tag{18}$$

where $\mathbf{M(q)}$ is the configuration-dependent mass (or inertia) matrix.

In terrestrial UGV applications, gravitational potential energy is the dominant component. For link i, if the vertical position of its center of mass is z_i, then

$$V_i = m_i g z_i, \tag{19}$$

with gg representing the gravitational acceleration. The total potential energy is therefore

$$\mathbf{V(q)} = \sum_{i=0}^{n} \mathbf{m_i g z_i} \tag{20}$$

In some designs, additional potential energy terms due to elastic elements (e.g., preloaded springs at the joints) may be incorporated into $\mathbf{V(q)}$.

The equations of motion are derived by applying the Euler-Lagrange equation for each generalized coordinate θ_i:

$$\frac{d}{dt}\left(\frac{\partial \pounds}{\partial \dot{\theta}_i}\right) - \frac{\partial \pounds}{\partial \theta_i} = \tau_i, \tag{21}$$

where τ_i represents the generalized torque applied at the i-th joint. For a passive Rocker-Bogie system, these torques often include contributions from joint stiffness and damping, modeled as

$$\tau_i = -k_i(\theta_i - \theta_{i,0}) - c_i\dot{\theta}_i, \tag{22}$$

with k_i and c_i denoting the stiffness and damping coefficients, and $\theta_{i,0}$ the equilibrium angle.

Substituting the expressions for T and V into the Euler-Lagrange equations results in a set of nonlinear second-order differential equations:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + K(q - q_0) + G(q) = \tau_{ext}, \tag{23}$$

where:

$C(q,\dot{q})$ represents the Coriolis and centrifugal terms,
$K(q - q_0)$ captures the restoring torques due to joint stiffness,
$G(q) = \nabla_q V(q)$ is the gravitational force vector,
τ_{ext} accounts for external torques (e.g., impacts from terrain irregularities).

Due to the complexity of the derived dynamic equations, numerical integration techniques such as Runge-Kutta methods are employed to simulate the suspension's transient behavior over time. These simulations help evaluate shock absorption performance, chassis oscillations, and energy dissipation under various terrain conditions. The insights gained from the dynamic analysis are crucial for both design optimization and the development of control strategies.

For safe and effective UGV operation, it is essential that the wheels remain in continuous contact with the terrain. This condition can be mathematically expressed as

$$z_i \geq z_{terrain}(x_i), \tag{24}$$

where z_i is the vertical position of the ii-th wheel and $z_{terrain}(x_i)$ is the terrain elevation at the corresponding horizontal location x_i. The kinematic design must ensure that even in the presence of disturbances, the overall configuration of the Rocker-Bogie system preserves sufficient wheel contact to maintain stability and traction. The static equilibrium configuration of the suspension corresponds to a local minimum of the potential energy $V(q)$. To analyze the stability of an equilibrium configuration q∗, we examine the Hessian matrix of the potential energy:

$$H(q^*) = \left.\frac{\partial^2 V}{\partial q^2}\right|_{q=q^*} \tag{25}$$

If $H(q^*)$ is positive definite, then small perturbations about q^* will be met with restoring forces that drive the system back to equilibrium. This analysis is particularly important for designing the elastic (spring) elements that contribute to the system's passive shock absorption.

The compliance of the Rocker-Bogie system is determined by the stiffness and damping properties of the joints. The joint torque model (see formula 22) illustrates how the system absorbs and dissipates energy. Performance metrics in this context include:
Peak Chassis Acceleration: Lower peak accelerations indicate better shock absorption.
Energy Dissipated: The energy absorbed by the damping elements during transient events quantifies the system's ability to smooth out disturbances.
Recovery Time: The rate at which the system returns to equilibrium after a shock is an important performance measure.

An important feature of the Rocker-Bogie mechanism is its kinematic redundancy. Multiple joint configurations can achieve the same wheel–terrain contact point. This redundancy allows designers to optimize for additional criteria such as:
Minimizing Energy Consumption: By selecting configurations that reduce the amount of motion or avoid extreme joint angles.
Maximizing Stability Margins: By choosing configurations that keep the center of gravity well within the support polygon.
Avoiding Singular Configurations: By steering clear of joint configurations where the Jacobian loses rank and the system becomes less controllable.

The analysis of the null space of the Jacobian matrix provides a mathematical basis for redundancy resolution.

To validate our mathematical model, we performed simulations using MATLAB.
The simulation environment incorporated multiple terrain profiles including a sinusoidal terrain described by

$$z_{terrain}\,(x) = \mathrm{A}\sin\left(\frac{2\pi x}{\lambda}\right) \tag{26}$$

where **A** is the amplitude and **λ** is the wavelength.

A. Jacobian Analysis and Inverse Kinematics Convergence

The Jacobian matrix J(q) was computed for various configurations. Near configurations where the determinant of **J(q)** approaches zero, the system is near a kinematic singularity; however, the damped least-squares inverse kinematics algorithm successfully converged in fewer than 20 iterations for typical test cases.

Dynamic simulations were performed to assess the response of the suspension to abrupt terrain changes. Time-history plots of chassis vertical acceleration indicate that the passive compliance inherent in the Rocker-Bogie design effectively attenuates high-frequency shocks. In one simulation, a sudden step obstacle produced peak accelerations that were reduced by over 50% due to the damping elements. Fourier analysis of joint motion confirmed that the system suppresses resonant frequencies, and energy dissipation analyses revealed that the damping parameters could be tuned to balance shock absorption with energy efficiency.

Sensitivity Analysis

A sensitivity study was conducted by varying key parameters (joint stiffness, damping coefficients, and link lengths) by ±10% and observing the effects on performance metrics.

Key findings include:

Stiffness Variations: A 10% reduction in stiffness increased wheel slip by approximately 15% on rough terrain, while a 10% increase reduced slip at the cost of higher impact forces.

Damping Variations: Increased damping improved shock absorption but reduced the system's responsiveness to rapid terrain changes.

Link Length Variations: Changes in link lengths altered the effective stride and the curvature of the wheel trajectories, impacting both stability margins and energy consumption.

B. *Integration of Mathematical and Kinematic Analyses*

The integrated mathematical framework presented in this paper unifies the kinematic and dynamic aspects of the Rocker-Bogie suspension. Our derivations for forward kinematics and the Jacobian matrix provide precise relationships between joint motions and wheel trajectories, ensuring that the UGV maintains continuous terrain contact. Meanwhile, the dynamic model derived using Lagrangian mechanics explains how the system absorbs shocks and dissipates energy. Together, these models offer a tool for both design optimization and control strategy development.

The Rocker-Bogie suspension offers significant advantages for UGV applications:

Continuous Wheel Contact: By ensuring that at least one wheel on each side remains in contact with the terrain, the design enhances traction and vehicle stability.

Passive Adaptability: The suspension adapts automatically to terrain irregularities, reducing the need for complex active control systems.

Energy Efficiency: The predominantly passive operation reduces power consumption a critical consideration for long-duration missions.

Robust Shock Absorption: The combination of elastic and damping elements effectively mitigates the impact of high-frequency disturbances.

Kinematic Redundancy: Multiple configurations can achieve the same wheel position, providing flexibility to optimize additional performance criteria.

These features are particularly important for UGVs operating in harsh and unpredictable environments, where reliability and efficiency are paramount.

C. *Challenges and Limitations*

Despite its many advantages, the Rocker-Bogie system also faces challenges:

Nonlinear Complexity: The derived kinematic and dynamic equations are highly nonlinear, which complicates real-time control and optimization.

Singular Configurations: The Jacobian matrix may approach singularity in certain configurations, reducing the system's controllability. Effective regularization techniques and adaptive control strategies are needed to overcome this limitation.

Parameter Sensitivity: The performance is highly sensitive to variations in joint stiffness, damping, and geometric parameters. Variations due to manufacturing tolerances or wear may necessitate periodic recalibration or adaptive parameter tuning.

Extension to Three Dimensions: While our planar analysis offers valuable insights, UGVs operate in a fully three-dimensional environment. Extending the model to capture spatial dynamics introduces additional complexity and computational challenges.

V. CONCLUSION

This paper has presented a new mathematical model and kinematic analysis of the Rocker-Bogie suspension design for UGV applications. Our work integrates detailed derivations of forward kinematics, the Jacobian matrix, and an iterative inverse kinematics algorithm with a dynamic model based on Lagrangian mechanics. Key conclusions are as follows:

The derived kinematic model accurately predicts the positions of wheel contact points, ensuring continuous terrain conformity.

The Jacobian matrix analysis provides insight into the sensitivity of the system and identifies potential singular configurations.

The dynamic model confirms that passive compliance—combined with appropriate damping—effectively attenuates shocks and reduces chassis oscillations.

Sensitivity analyses underscore the importance of precise parameter calibration and highlight opportunities for adaptive control.

Kinematic redundancy inherent in the Rocker-Bogie design offers flexibility for optimizing additional performance criteria such as energy consumption and stability.

Overall, the integrated framework developed herein lays a robust foundation for both the design and control of Rocker-Bogie UGVs operating in challenging environments.

This paper presents a rigorous, integrated mathematical framework for the analysis and design of Rocker-Bogie suspension systems for UGVs. By combining detailed kinematic formulations with dynamic modeling via Lagrangian mechanics, we have developed a foundation for understanding the complex interactions within the suspension. Simulation studies validate the theoretical models and highlight the importance of parameter tuning and adaptive control strategies. The insights provided here are intended to inform future research and development efforts aimed at optimizing UGV performance in challenging, unstructured environments.

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