

Article

Design and Structural Evaluation of an Adaptive Traction Rover Wheel for Lunar Mobility Applications

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Abstract.

Lunar rover wheels must combine low mass, traction, compliance, abrasion resistance, and maintainability under vacuum, thermal cycling, and unconsolidated regolith. This study develops and evaluates an adaptive traction rover wheel for lunar surface mobility applications. The method combined requirement definition, terramechanics-based grouser sizing, material selection, CAD-based structural packaging, finite element evaluation, manufacturability assessment, and service-life estimation. The proposed wheel uses a two-piece Ti-6Al-4V rim, ten alternating compliant titanium spokes, ten 27 mm V-shaped grousers, a 6061-T6 aluminum hub, riveted mechanical joints, and Cr3C2-NiCr HVOF coating on soil-contact surfaces. The design achieved a diameter of 0.457 m, a width of 0.203 m, and a total mass of 2.254 kg. Linear-elastic structural screening indicated that the wheel supported a nominal normal load of 256 N with a factor of safety of approximately 2 based on a minimum Ti-6Al-4V yield-strength criterion of 828 MPa. The 3 g impact screening case produced a local peak von Mises stress of approximately 900 MPa, exceeding this conservative yield criterion and therefore requiring nonlinear analysis and experimental validation. Traction capability, wear resistance, and 1,000 km service-life estimates are analytical projections derived from geometry and wear modeling, not fully validated operational performance. The proposed architecture is therefore a lightweight, repairable, and traction-oriented wheel concept requiring targeted laboratory validation before mission use.

Keywords: lunar rover wheel; compliant wheel; Ti-6Al-4V; terramechanics; finite element analysis

INTRODUCTION

Surface mobility is a critical subsystem for robotic and crew-assisted lunar exploration because the wheel-terrain interface determines traversability, energy demand, localization stability, and mission productivity. Lunar rover

wheels must operate on granular regolith under low gravity, angular abrasive particles, uncertain bearing strength, vacuum exposure, and extreme thermal cycling. Classical terramechanics provides the basis for understanding wheel sinkage, slip, drawbar pull, and contact mechanics on deformable terrain, while lunar soil studies show that regolith has irregular particle morphology and high abrasiveness that can accelerate wear of exposed mobility components [1], [2], [3], [4], [5].

Historical rover wheel designs show that no single architecture fully resolves the competing requirements of low mass, traction, compliance, dust mitigation, and maintainability. The Apollo Lunar Roving Vehicle employed wire-mesh wheels with chevron tread elements to provide lightweight compliance, while later rigid metallic wheels offered dimensional stability but were more vulnerable to local puncture, fatigue cracking, and stress concentration under repeated rock contact. Recent compliant and superelastic tire concepts have improved deformation tolerance, but some designs remain difficult to repair locally because the wheel body is integrated as a monolithic structure [6], [7], [8], [9], [10].

For small and medium rover classes, a wheel architecture that integrates structural compliance directly into the wheel can reduce impact transmission to the chassis while improving terrain conformity. Compliant spokes and non-pneumatic tires have been studied as alternatives to conventional rigid wheels because deformation can passively absorb vertical disturbances and expand the effective contact patch. However, the geometry of the compliant members must be selected carefully: excessive flexibility increases rolling resistance and sinkage, whereas excessive stiffness reduces shock absorption and may concentrate stress at the hub-rim interface [8], [10], [11], [12]

Traction on loose regolith depends strongly on tread geometry. Grousers increase shear interaction with soil, but their height, pitch, and shape affect sinkage, slip, driving torque, and side force. Experimental studies on grouser wheels have demonstrated that grouser shape changes the distribution of soil reaction forces and that chevron or V-shaped geometries can improve longitudinal traction and directional stability in granular media. In addition, open tread and rim geometries can help limit dust retention by allowing granular material to escape during wheel rotation [2], [11], [12], [13].

Although previous studies have investigated compliant spokes, non-pneumatic metallic wheels, or grouser geometries separately, a research gap remains in integrating these functions into a modular wheel architecture that simultaneously addresses compliant load transfer, traction-oriented tread geometry, abrasive-wear protection, vacuum-compatible joining, and component-level replacement for lunar mobility.

The novelty of this study is the integrated adaptive traction wheel concept, which combines a two-piece Ti-6Al-4V rim, alternating compliant titanium spokes, replaceable V-shaped grousers, a lightweight 6061-T6 hub, riveted joints, and Cr3C2-NiCr coating within one repair-oriented assembly. Accordingly, the objective was to define the wheel architecture and to conduct preliminary structural, mass, manufacturability, and analytical wear assessments; traction, abrasion resistance, and service-life performance were not experimentally validated in this study.

METHODS

Research Design and Design Requirements

This work was conducted as an engineering design research study. The research sequence consisted of defining lunar mobility requirements, translating them into wheel-level design constraints, developing a modular wheel architecture, selecting metallic materials suitable for vacuum and thermal cycling, evaluating structural behavior using finite element analysis, and assessing manufacturability and service life. The primary design outputs were wheel geometry, material selection, grouser configuration, spoke compliance, mass distribution, joint strategy, and replaceability.

The target configuration was a drum-type rover wheel with an outer diameter of approximately 0.457 m and a width of 0.203 m. The design load was defined as 256 N per wheel under nominal operation, with a 3g impact case represented by 768 N. The wheel was required to remain below 2.3 kg, climb a 20° slope on loose regolith simulant with limited slip, provide passive compliance during obstacle traversal, and avoid adhesives, lubricants, and polymers to reduce outgassing risk in vacuum [14], [15], [16], [17], [18], [19].

Table 1. Main design requirements used for the adaptive rover wheel

Parameter	Target or assumption	Design rationale
Outer diameter	0.457 m	Balances obstacle traversal, mass, and packaging
Wheel width	0.203 m	Provides contact width without excessive mass
Maximum mass	< 2.3 kg per wheel	Supports lightweight rover mobility
Nominal normal load	256 N	Represents wheel-level design load
Impact load case	768 N (3g)	Represents shock event during mobility
Slope target	20°	Mobility requirement on loose regolith
Joining method	Mechanical rivets	Avoids welds, adhesives, and lubricants

Grouser and Compliance Sizing

Grouser design was guided by terramechanics considerations and comparative studies of grouser shapes on sandy terrain. The preliminary grouser height ratio was calculated using the relationship in Equation (1), where h_g is

grouser height and D is wheel diameter. For the present design, the 27 mm grouser height and 457 mm wheel diameter produced $h_g/D = 0.059$. This value is slightly above commonly recommended preliminary ranges, providing additional margin for wear while maintaining soil-engagement capability.

$$\frac{h_g}{D} = 0.059 \quad (1)$$

Equation (1) was used to check the proportionality of grouser height relative to wheel diameter. Equation (2) was used to interpret the structural safety margin from finite element stresses. Equation (3) defines the effective radial stiffness based on load and deflection, while Equation (4) estimates the number of wheel rotations for a given travel distance.

$$FoS = \frac{\sigma_y}{\sigma_{max}} \quad (2)$$

$$k_{eff} = \frac{F}{\delta} \quad (3)$$

$$N_{rot} = \frac{L}{\pi \cdot D} \quad (4)$$

Material, Structural, and Manufacturing Assessment

Ti-6Al-4V was selected for the rim, spokes, and grousers because of its high specific strength, fatigue resistance, corrosion resistance, and mechanical stability across cryogenic-to-elevated temperature ranges. Aluminum 6061-T6 was selected for the hub to reduce rotational mass and exploit its machinability. The material comparison considered density, yield strength, modulus, thermal expansion, conductivity, and service-temperature compatibility [20], [21], [22], [23], [24], [25].

Structural evaluation focused on static normal loading and a 3g impact load case. The finite element model treated the rim, spoke, and hub assembly as the primary load path. Design acceptability was assessed by maximum stress, radial deflection, factor of safety, and compatibility with expected elastic-plastic deformation limits. Manufacturing assessment followed DFMA principles, including part-count reduction, repeated geometry, standard machining operations, and accessible mechanical fasteners [16], [18], [26], [27], [28].

Wear and service-life assessment was based on the assumed Cr3C2-NiCr coating thickness, estimated abrasive wear rate, and residual grouser height. Archard-type wear reasoning was used as a first-order model for material loss under abrasive contact, while coating selection was supported by published HVOF coating studies and tribology references [29], [30], [31], [32], [33], [34], [35]

Finite Element Analysis Setup

A static, linear-elastic finite element model of the rim-spoke-hub load path was used as a preliminary structural-screening analysis. The central hub/axle interface was constrained in all translational directions, and the applied vertical load was represented as a downward distributed force over the lower rim-ground-contact region. Two load cases were evaluated: a nominal wheel load of 256 N and a 3 g impact-screening load of 768 N.

Structural acceptability was evaluated using maximum von Mises stress, radial deflection, and factor of safety, calculated as $FoS = \sigma_y / \sigma_{vM,max}$. The conservative material criterion was the minimum room-temperature Ti-6Al-4V yield strength of 828 MPa reported in Table 2. A nominal-load target of $FoS \geq 2$ was used for screening, whereas the 3 g condition was used to identify high-stress regions requiring nonlinear analysis and experimental verification. Manufacturing assessment followed DFMA principles, including part-count reduction, repeated geometry, standard machining operations, and accessible mechanical fasteners [16], [18], [24], [27], [28].

Table 2. Material properties considered for the main wheel components

Property	Aluminum 6061-T6	Ti-6Al-4V
Density	2.70 g/cm ³	4.43 g/cm ³
Yield strength	276 MPa	828 MPa
Ultimate tensile strength	310 MPa	900-950 MPa
Elastic modulus	69 GPa	110 GPa
Elongation at break	12%	10-14%
Thermal expansion	23.6 $\mu\text{m/m } ^\circ\text{C}$	8.6 $\mu\text{m/m } ^\circ\text{C}$
Recommended service temperature	up to 150 $^\circ\text{C}$	up to 350 $^\circ\text{C}$

Wear and service-life assessment was based on the assumed Cr₃C₂-NiCr coating thickness, estimated abrasive wear rate, and residual grouser height. Archard-type wear reasoning was used as a first-order model for material loss under abrasive contact, while coating selection was supported by published HVOF coating studies and tribology references.

RESULT AND DISCUSSION

Wheel Architecture and Modular Layout

The resulting wheel is a modular drum-type assembly shown in Figure 1 composed of two Ti-6Al-4V rim half-rings, ten curved compliant spokes, ten external V-shaped grousers, and a 6061-T6 aluminum central hub. The two-piece rim simplifies assembly because the spokes and grousers can be positioned between the rim halves and fastened mechanically. This arrangement also allows component-level replacement if a spoke, grouser, or rim segment experiences excessive wear or local damage.

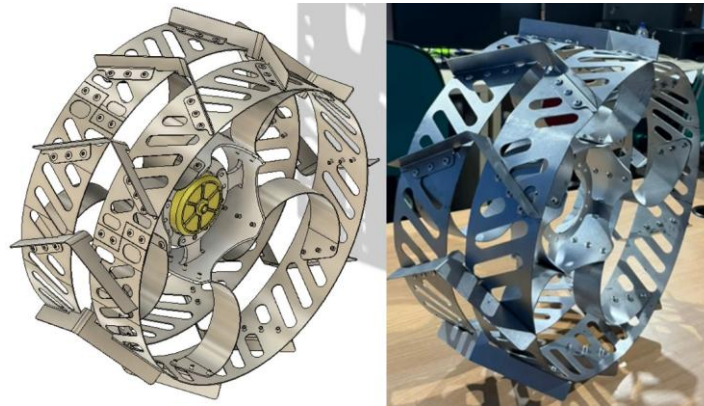


Figure 1. Adaptive traction rover wheel design and prototype configuration

The open architecture is important for lunar mobility because trapped regolith can increase rolling resistance and accelerate abrasive wear. In the proposed layout, the spaces between spokes and grousers allow particles to leave the wheel during rotation. The wheel center of mass is aligned with the rotational axis, supporting dynamic balance and reducing parasitic vibration during operation.

Mass Distribution and Material Selection

The total wheel mass was 2.254 kg, satisfying the 2.3 kg mass target. Titanium components dominate the mass because they form the primary structural and traction interfaces, whereas the aluminum hub reduces inertia near the axle. The mass distribution listed in Table 3 indicates that structural efficiency depends not only on material density but also on allowing thin high-strength Ti-6Al-4V members to carry rim and spoke loads.

Table 3. Mass distribution of the adaptive traction rover wheel

Component	Material	Mass (g)	Function
Rim half-rings	Ti-6Al-4V	794	Outer structure and spoke/grouser interface
Compliant spokes (10)	Ti-6Al-4V	510	Load-bearing flexural elements
Grousers (10)	Ti-6Al-4V + Cr3C2-NiCr	415	Traction and sacrificial wear elements
Hub bracket	Aluminum 6061-T6	444	Axle interface and torque transfer
Rivets (88)	Ti-6Al-4V	63.6	Mechanical fastening
Total	Mixed metallic assembly	2253.6	Mass below 2.3 kg target

Traction-Oriented Grouser Design

Ten V-shaped grousers were distributed uniformly around the wheel circumference. Each grouser extends 27 mm radially from the rim, producing a grouser-height-to-wheel-diameter ratio of 0.059. The V-shaped geometry is intended to redirect soil reaction components downward and rearward,

providing an analytical basis for increased shear engagement and lower longitudinal slip relative to simple flat tread profiles. The spacing also maintains repeated terrain contact without fully closing the outer rim, which is intended to promote dust shedding. These traction and dust-shedding effects require soil-bin validation with lunar regolith simulants.

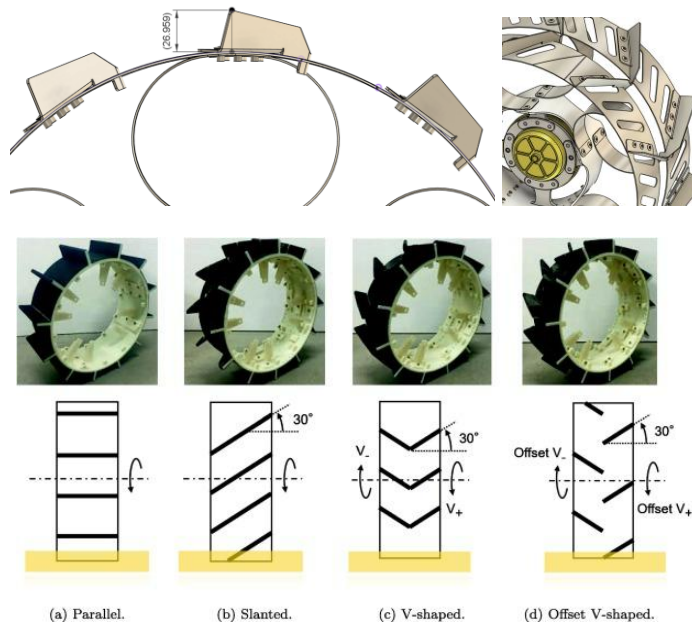


Figure 2. V-shaped grouser geometry and circumferential positioning on the wheel rim

The selected grouser height exceeds the minimum value indicated by classical grouser-ratio guidance, which is advantageous for wear margin. However, excessive grouser height can increase sinkage and driving torque. Therefore, future soil-bin testing should quantify the actual drawbar pull, sinkage, and slip ratio using lunar regolith simulants under reduced-gravity equivalent loading.

Compliant Spoke Behavior and Structural Response

The wheel uses ten curved Ti-6Al-4V spokes arranged in alternating clockwise and counterclockwise orientations. This configuration distributes stiffness in both driving directions and provides a compliant load path between the hub and rim. The curvature radius controls stiffness: larger curvature reduces local reaction force and increases compliance, while smaller curvature produces a stiffer response. This passive compliance can reduce impact transmission to the rover chassis while maintaining ground contact on uneven terrain.

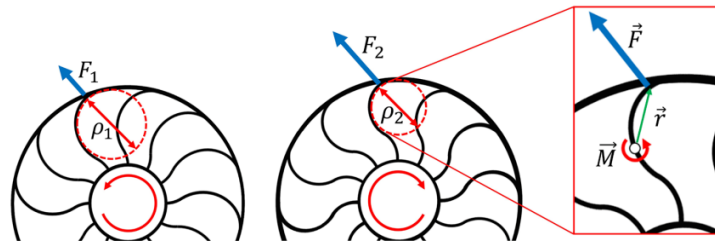


Figure 3. Relationship between spoke curvature and stiffness in compliant wheel structures

Under the static nominal load of 256 N, the reported factor of safety of approximately 2 corresponds to a peak von Mises stress of about 414 MPa when calculated using the conservative minimum room-temperature Ti-6Al-4V yield strength of 828 MPa reported in Table 2 ($FoS = \sigma_y / \sigma_{vM, max}$). Under the 3 g impact-screening load of 768 N, the model predicts a localized peak von Mises stress of approximately 900 MPa. This value exceeds the 828 MPa yield-strength criterion and should not be described as remaining within the yield range or as evidence of validated impact capability. The resulting impact FoS is approximately 0.92; therefore, localized yielding may occur in the linear-elastic model. Because 900 MPa also approaches the reported 900–950 MPa ultimate-tensile-strength range, the impact result should be treated as a screening flag requiring geometry refinement, nonlinear material modeling, and physical impact testing. The predicted radial deformation of 8–17 mm represents analytical compliance and should likewise be verified by cyclic radial-loading tests.

Table 4. Summary of structural and mobility-related outcomes

Evaluation item	Result	Interpretation
Nominal vertical load	256 N	Supported with FOS about 2
Impact load case	768 N	Equivalent to 3g wheel-level shock
Maximum impact stress	900 MPa	Below or near Ti-6Al-4V yield range; no catastrophic failure predicted
Radial compliance	8-17 mm	Provides shock absorption and terrain conformity
Center-of-mass offset	0-1 mm	Supports balanced rotation
Slope capability target	20 °	Supported by traction-oriented grouser geometry
Predicted mission distance	1000 km	Residual grouser height remains functional

Manufacturability, Assembly, and Serviceability

The design uses conventional fabrication routes: CNC machining for rim and hub components, laser cutting and bending for spokes and grousers, HVOF spraying for the wear coating, and riveted assembly for all major joints. This process chain avoids casting, welding, adhesives, and lubricants. The absence

of adhesives and lubricants is beneficial for vacuum compatibility, while the absence of welding avoids heat-affected zones in titanium components.

DFMA considerations were incorporated by reducing the number of unique structural parts, repeating identical spokes and grousers, using two similar rim halves, and applying a common rivet strategy. The prototype demonstrated that assembly can be completed using basic mechanical tools, and the report data indicate that the prototype wheel could be produced within several hours. From a maintenance perspective, the architecture supports localized component replacement rather than full wheel replacement.

Environmental Compatibility and Service-Life Estimation

All primary structural components are metallic, which reduces outgassing concerns in vacuum. Ti-6Al-4V and Aluminum 6061-T6 retain useful mechanical properties over the expected lunar day-night temperature range. Differential thermal expansion between titanium and aluminum is a design concern, but the mechanically fastened hub-spoke interface can accommodate limited micro-slip and elastic relief during thermal cycling. Nevertheless, thermal-vacuum cycling remains a necessary verification step before mission use.

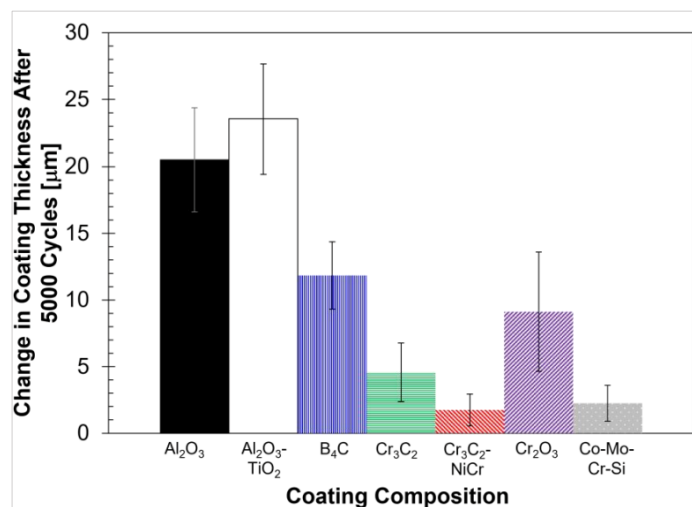


Figure 4. Relative coating-thickness change after abrasive wear testing of candidate coatings

A Cr₃C₂-NiCr HVOF coating was selected for soil-contact surfaces to reduce abrasive wear. The coating is intended to protect the grousers and rim edges from angular regolith particles. The stated coating wear-through distance of approximately 482 km and the residual grouser height of approximately 17 mm after a 1,000 km traverse are analytical estimates derived from assumed coating thickness, abrasive-wear rate, and residual geometric height; they are not measurements of operational wear resistance or validated wheel service life. Consequently, the 1,000 km value should be interpreted as a preliminary service-life projection only.

Using Equation (4), a 1,000 km traverse corresponds to approximately 696,500 wheel rotations for a 0.457 m diameter wheel. This cyclic count is a planning input for future fatigue testing of the spoke and rivet interfaces, not a validated fatigue-life result. Required verification includes regolith-drum wear testing, cyclic radial loading, lateral-load testing, drop-impact testing, thermal-vacuum cycling, and post-test inspection of rivet preload and residual spoke deformation.

CONCLUSION

This study presented the design and structural evaluation of an Adaptive Traction Rover Wheel for lunar mobility applications. The wheel integrates a modular Ti-6Al-4V rim, alternating compliant titanium spokes, 27 mm V-shaped grousers, a lightweight 6061-T6 aluminum hub, riveted joints, and Cr3C2-NiCr HVOF coating on soil-contact surfaces. The architecture addresses traction, compliance, dust mitigation, wear resistance, mass control, and maintainability within a single wheel assembly.

The design achieved a total mass of 2.254 kg, below the 2.3 kg target, and finite element evaluation indicated acceptable structural margin under nominal and impact load cases. The compliant spoke configuration provides passive radial deformation, while the open rim and grouser layout support passive dust shedding. Service-life estimation suggests that the wheel can retain functional grouser height after a 1000 km traverse, although this prediction requires experimental confirmation.

Future research should focus on soil-bin traction testing using lunar regolith simulants, thermal-vacuum cycling, accelerated abrasive wear testing, fatigue testing of spokes and riveted joints, and dynamic rover-level mobility trials. These steps are necessary to transition the proposed design from analytical and prototype-level validation toward flight-representative qualification

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REFERENCES

- [1] M. G. Bekker, *Introduction to Terrain-Vehicle Systems*. Ann Arbor, MI, USA: University of Michigan Press, 1969.
- [2] J. Y. Wong, *Theory of Ground Vehicles*, 4th ed. Hoboken, NJ, USA: John Wiley & Sons, 2008.
- [3] G. H. Heiken, D. T. Vaniman, and B. M. French, Eds., *Lunar Sourcebook: A User's Guide to the Moon*. Cambridge, UK: Cambridge University Press, 1991.

- [4] I. I. I. Carrier W. D., G. R. Olhoeft, and W. Mendell, "Physical Properties of the Lunar Surface," in *Lunar Sourcebook: A User's Guide to the Moon*, G. H. Heiken, D. T. Vaniman, and B. M. French, Eds., Cambridge, UK: Cambridge University Press, 1991, pp. 475–594.
- [5] J. R. Gaier, "The Effects of Lunar Dust on EVA Systems During the Apollo Missions," Cleveland, OH, USA, 2005. [Online]. Available: <https://ntrs.nasa.gov/citations/20050160460>
- [6] N. C. Costes, I. I. I. Carrier W. D., J. K. Mitchell, and R. F. Scott, "Mobility Performance of the Lunar Roving Vehicle: Terrestrial Studies---Apollo 15 Results," 1972. [Online]. Available: <https://ntrs.nasa.gov/citations/19730008090>
- [7] R. A. Creel, "Applying Thermal Control Experiences on the Apollo Rover Project to Rovers for Future Space Exploration." Aug. 2007. [Online]. Available: https://apollojournals.org/alsj/creel_lrv_experiences_alsj.pdf
- [8] NASA Glenn Research Center, "Superelastic Tire." 2017. [Online]. Available: <https://technology.nasa.gov/patent/LEW-TOPS-99>
- [9] H. Yoon, K. Lee, J. Lee, J. Kwon, and T. Seo, "The Stiffness Adjustable Wheel Mechanism Based on Compliant Spoke Deformation," *Sci. Rep.*, vol. 14, no. 1, p. 773, 2024, doi: 10.1038/s41598-024-51493-x.
- [10] K. Nagaoka, K. Sawada, and K. Yoshida, "Shape Effects of Wheel Grousers on Traction Performance on Sandy Terrain," *J. Terramechanics*, vol. 90, pp. 23–30, 2020, doi: 10.1016/j.jterra.2019.08.001.
- [11] A. N. Ibrahim, S. Aoshima, N. Shiroma, and Y. Fukuoka, "The Effect of Assistive Anchor-Like Grousers on Wheeled Rover Performance over Unconsolidated Sandy Dune Inclines," *Sensors*, vol. 16, no. 9, p. 1507, 2016, doi: 10.3390/s16091507.
- [12] X. Dong, Y. Li, and Z. Zhang, "Study on the Influence of Rigid Wheel Surface Structure on the Trafficability of Planetary Rover on Soft Ground," *Aerospace*, vol. 12, no. 4, p. 305, 2025, doi: 10.3390/aerospace12040305.
- [13] S. Moreland, K. Skonieczny, H. Inotsume, and D. Wettergreen, "Soil Behavior of Wheels with Grousers for Planetary Rovers," in *2012 IEEE Aerospace Conference*, Big Sky, MT, USA, 2012, pp. 1–8. doi: 10.1109/AERO.2012.6187040.
- [14] NASA Exploration Systems Mission Directorate, "Lunar Environmental Characterization for Surface Systems," 2007.
- [15] National Aeronautics and Space Administration, "Payload Vibroacoustic Test Criteria," 2017.
- [16] NASA Office of the Chief Engineer, *NASA Systems Engineering Handbook*, Rev. 2., no. NASA/SP-2016-6105. Washington, DC, USA: National Aeronautics and Space Administration, 2016. [Online]. Available: <https://www.nasa.gov/reference/systems-engineering-handbook/>
- [17] G. Boothroyd, P. Dewhurst, and W. A. Knight, *Product Design for Manufacture and Assembly*, 3rd ed. Boca Raton, FL, USA: CRC Press, 2011.
- [18] R. T. Barrett, "Fastener Design Manual," 1990. [Online]. Available: <https://ntrs.nasa.gov/citations/19900009424>

- [19] ASTM International, “{ASTM E595-19}: Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment,” West Conshohocken, PA, USA, 2019.
- [20] R. F. Muraca and J. S. Whittick, “Materials Data Handbook: Titanium 6Al-4V,” 1972.
- [21] E. D. Marquardt, J. P. Le, and R. Radebaugh, “Cryogenic Material Properties Database,” in *Cryocoolers 11*, J. Ross R. G., Ed., Boston, MA, USA: Springer, 2002, pp. 681–687. doi: 10.1007/0-306-47112-4_84.
- [22] TIMET, “{TIMETAL 6-4}: Properties and Processing Information,” Dallas, TX, USA, 2022.
- [23] Kaiser Aluminum, “6061-T6 Aluminum Product Data Sheet,” Foothill Ranch, CA, USA, 2021.
- [24] ASM International Handbook Committee, *ASM Handbook, Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys*. Materials Park, OH, USA: ASM International, 1990.
- [25] K. C. Ludema, *Friction, Wear, Lubrication: A Textbook in Tribology*. Boca Raton, FL, USA: CRC Press, 1996.
- [26] ASM International Handbook Committee, *ASM Handbook, Volume 19: Fatigue and Fracture*. Materials Park, OH, USA: ASM International, 1996.
- [27] G. W. Stachowiak and A. W. Batchelor, *Engineering Tribology*, 4th ed. Oxford, UK: Butterworth-Heinemann, 2013.
- [28] J. F. Archard, “Contact and Rubbing of Flat Surfaces,” *J. Appl. Phys.*, vol. 24, no. 8, pp. 981–988, 1953, doi: 10.1063/1.1721688.
- [29] B. Seitov et al., “Review of Physical and Mechanical Properties, Morphology, and Phase Structure in Cr₃C₂-NiCr Composite Coatings Sprayed by HVOF Method,” *Coatings*, vol. 15, no. 4, p. 479, 2025, doi: 10.3390/coatings15040479.
- [30] S. Mahade, A. Mulone, S. Björklund, U. Klement, and S. Joshi, “Investigating Load-Dependent Wear Behavior and Degradation Mechanisms in Cr₃C₂-NiCr Coatings Deposited by HVOF and HVOF,” *J. Mater. Res. Technol.*, vol. 15, pp. 4595–4609, 2021, doi: 10.1016/j.jmrt.2021.10.088.
- [31] ASTM International, “{ASTM G99-17}: Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus,” West Conshohocken, PA, USA, 2017.
- [32] ASTM International, “{ASTM G65-16}: Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus,” West Conshohocken, PA, USA, 2016.
- [33] National Aeronautics and Space Administration, *NASA Cost Estimating Handbook, Version 4.0*. Washington, DC, USA: National Aeronautics and Space Administration, 2015. [Online]. Available: <https://www.nasa.gov/ocfo/ppc-corner/nasa-cost-estimating-handbook-ceh/>
- [34] ECSS Secretariat, “Space Engineering: Mechanisms,” Noordwijk, The Netherlands, 2019. [Online]. Available: <https://ecss.nl/standard/ecss-e-st-33-01c-rev-2-1-march-2019-space-engineering-mechanisms/>
- [35] National Aeronautics and Space Administration, “Standard Materials and Processes Requirements for Spacecraft,” 2016.