Enhancing the Structural Integrity and Performance of an Agricultural Robot with Caterpillar Tracks: A Comprehensive Deformation Analysis

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Received: 4 May 2024 | Revised: 25 May 2024 | Accepted: 2 June 2024

ABSTRACT

The robustness and longevity of agricultural robots, specifically those utilizing caterpillar tracks for coconut harvesting, are based on understanding their strain, stress, and load thresholds. This study delves into the deformation characteristics of caterpillar track systems, pinpointing critical structural vulnerabilities and potential points of failure. Through a meticulous analysis of the maximum allowed strain and stress thresholds, this study unravels crucial insights to enhance performance and reliability in coconut field operations. Leveraging the power of ANSYS for structural analysis and simulation under varied constraints, this study aims to fortify the structural integrity of agricultural robots. By offering valuable insights and solutions, this study paves the way for advancements in agricultural robotics technology, ensuring that these machines can endure rigorous tasks while maintaining peak functionality.

Keywords-agricultural robot; caterpillar tracks; transportation; deformation analysis; ANSYS

I. INTRODUCTION

India's economy is highly dependent on agriculture, which supports approximately 54.6% of its population and significantly affects socioeconomic development [1, 2]. India excels in agricultural production, leading worldwide in milk, pulses, and jute, and ranking second in rice, wheat, sugarcane, groundnuts, vegetables, fruits, and cotton [3]. Additionally, it is a major producer of spices, fish, poultry, livestock, and plantation crops. Approximately 27 million hectares of land are allocated for horticultural crop production, contributing significantly to the agricultural landscape [2]. Horticulture crops include fruits, vegetables, aromatics, medicinal plants, flowers, honey, spices, and plantation crops. Coconut and areca nuts are among the most produced plantation crops in India [4]. Today, more than 50% of India's population depends on agriculture, with farmers making up the majority. However, the reliance on unskilled labor for various agricultural tasks adds an economic burden to farmers, in addition to the costs incurred for pesticides, irrigation facilities, and machinery. Agricultural robotics has been developed to alleviate the financial burden on farmers by assisting them in various agricultural activities. Agricultural exports are of significant importance in India, especially in the southern states, where a substantial part of the population depends on this crop [5].

Coconuts thrive in coastal areas and various soil types [6], offering numerous health benefits, including those of coconut oil, which has several medicinal properties [7]. Kerala, a leading state in Ayurveda, boasts a large coconut production and uses coconuts extensively in Ayurvedic applications [8]. Technological advances have led to unique harvesting methods for coconuts and other crops, improving productivity [4, 9]. These innovative techniques have been deployed beyond coconuts to benefit other agricultural sectors as well [10, 11]. This study investigates the deformation characteristics and structural integrity of caterpillar track systems in agricultural robots for coconut harvesting, employing ANSYS for advanced structural analysis and simulation to enhance their performance and reliability in the field.

II. LITERATURE SURVEY - INSPIRATION FOR CATERBOT

The two primary methods of carrying loads on farms are manual labor and wheeled vehicles [12, 13]. Manual labor, although traditional, causes health problems among farmers [12, 13]. Alternatively, wheeled vehicles, such as wagons, carts, and tractors, are used, with over 80% of farm production transported by animal-drawn carts [14, 15]. However, challenges such as human intervention, time consumption, and environmental concerns associated with fossil fuel usage make this option less efficient [17]. The advancement of agriculture machines has led to the emergence of various advanced tools suitable for different agricultural activities [18, 19]. However, these machines require significant investment and maintenance, adding an economic burden for farmers [19]. Agricultural robots have been developed for various tasks including harvesting, pesticide spraying, and irrigation, addressing specific agricultural needs [18, 19]. Recent advances in plant biology have led to the synthesis of plant seeds capable of thriving under diverse conditions, expanding agricultural possibilities worldwide [20]. However, most current agricultural robots are wheel-based, which can be inefficient on certain soil profiles and terrains [23, 24]. The differential drive mechanism employed in these robots may limit their maneuverability, leading to potential issues in the navigation of uneven terrain [25].

A unique solution to the challenges of navigating uneven terrain in agriculture involves the use of caterpillar tracks instead of wheels. Caterpillar tracks, commonly seen in military tanks, provide effective movement in various terrains due to their continuous belt-like structure [26, 27]. They have been previously implemented in agricultural vehicles, such as tractors, and continue to be used in modern applications [28-30]. The studies in [30, 31] provide comprehensive reviews of safety standards and the safety of automated agricultural machinery, highlighting the critical importance of collision avoidance systems to ensure safe operation of agricultural robots. A new robot named Caterbot (Caterpillar track + Robot) has been developed to address these navigation challenges, specifically designed to transport loads such as coconuts across varied terrain. This study subjects the Caterbot design model to static structural analysis to ensure reliability and strength, including Finite Element Method (FEM) analysis for deformation using ANSYS.

III. CATERBOT DESIGN AND DEVELOPMENT

Caterbot, designed to transport coconuts, operates on caterpillar tracks to navigate challenging terrain, offering ease of use to farmers. It features an electrical, lightweight, and cost-effective design, powered by rechargeable batteries, ensuring operation for up to six hours on a single charge. With corrosion resistance and suitability for any soil profile or climatic condition, Caterbot improves efficiency and longevity in agricultural operations, particularly coconut harvesting.

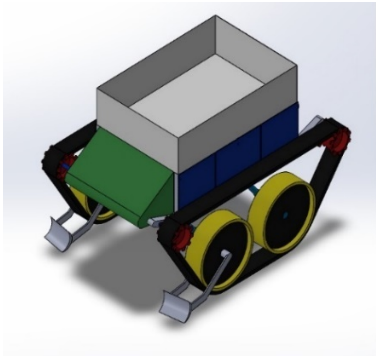


Fig. 1. Isometric view of Caterbot.

Figure 1 shows an isometric view of the Caterbot. Figure 2 illustrates an exploded view, showing all its components separated and arranged to display their relationships and assembly order. This detailed representation helps in understanding the internal structure and how each part fits together within it. This study aims to understand the strain, stress, and load thresholds of Caterbot components, particularly the caterpillar track system, through a comprehensive structural analysis using ANSYS to identify critical vulnerabilities and potential points of failure. Simulating its performance under different conditions and stresses can indicate areas for improvement to enhance performance and reliability in coconut field operations. Based on this analysis, strategies can be proposed to strengthen its structural integrity through material selection, design modifications, or reinforcement techniques, aiming to enhance its durability and functionality for more efficient and reliable operations. The mechanical properties overview in Figures 4, 5, and 6 illustrate material usage in Caterbot.

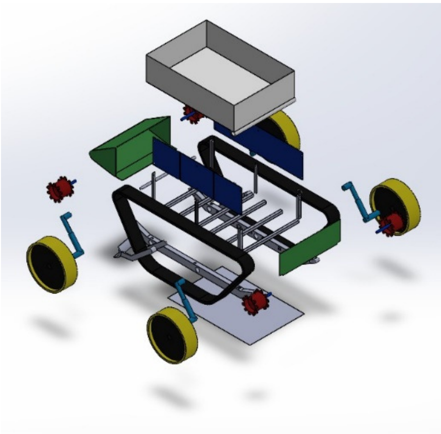


Fig. 2. Exploded view of Caterbot.

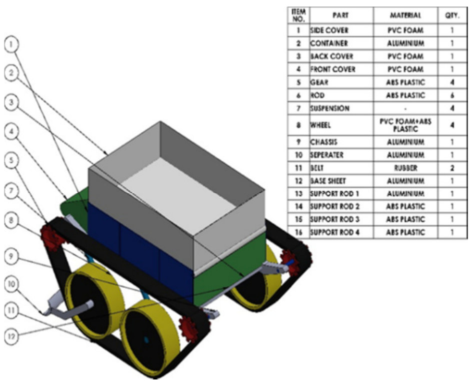


Fig. 3. Isometric view of Caterbot with material information.

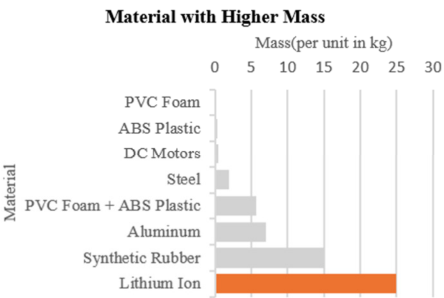


Fig. 4. Overview of the mechanical properties of Caterbot.

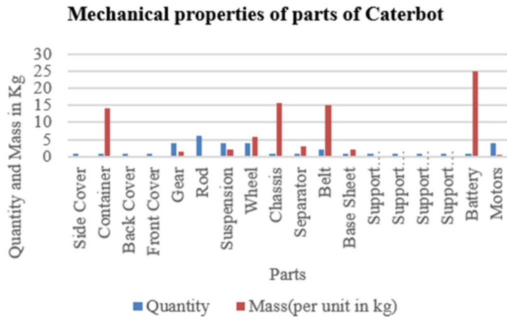


Fig. 5. Percentage distribution of materials used in Caterbot.

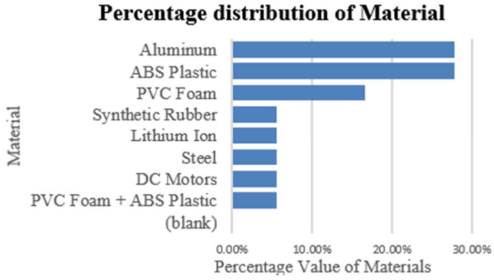


Fig. 6. Materials with higher mass used in the Caterbot.

IV. DESIGN SIMULATION AND ANALYSIS

Static structural analysis predicts a structure's response to applied loads without considering time or motion, aiding in design optimization. Caterbot was analyzed to evaluate its ability to achieve the objectives under specified conditions. ANSYS static structural analysis considers key parameters, such as force, fixed support, earth gravity, and acceleration, to evaluate its behavior under specified conditions, including payload weight, stationary support, gravitational force, and internal component weight. The analysis reveals stress, strain, and deformation distributions within Caterbot components, helping to evaluate structural integrity, identify weaknesses, and optimize design for enhanced performance in coconut harvesting operations.

TABLE I. MECHANICAL PROPERTIES OF CATERBOT PARTS

	Part	Material	Quantity	Mass (per unit in kg)
1	Side Cover	PVC Foam	1	0.13958
2	Container	Aluminum	1	14.121
3	Back Cover	PVC Foam	1	0.080016
4	Front Cover	PVC Foam	1	0.30746
5	Gear	ABS Plastic	4	1.39924
6	Rod	ABS Plastic	6	0.16751
7	Suspension	Steel	4	2
8	Wheel	PVC Foam + ABS Plastic	4	5.64453
9	Chassis	Aluminum	1	15.615
10	Separator	Aluminum	1	2.925
11	Belt	Synthetic Rubber	2	15
12	Base Sheet	Aluminum	1	2.0043
13	Support Rod 1	Aluminum	1	0.15
14	Support Rod 2	ABS Plastic	1	0.058084
15	Support Rod 3	ABS Plastic	1	0.047075
16	Support Rod 4	ABS Plastic	1	0.094005
17	Battery	Lithium Ion	1	25
18	Motors	DC Motors	4	0.5

V. RESULTS AND DISCUSSIONS:

After simulation, the following results were obtained: total deformation, directional deformation, equivalent stress, and equivalent elastic strain. The parameters that were analyzed while carrying out the static structural analysis of Caterbot with a payload of 80 Kg and the results are shown in the following figures and subsections.

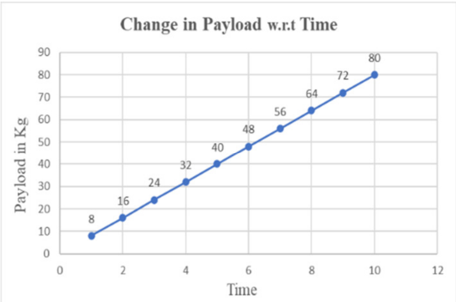


Fig. 7. Change in payload versus time.

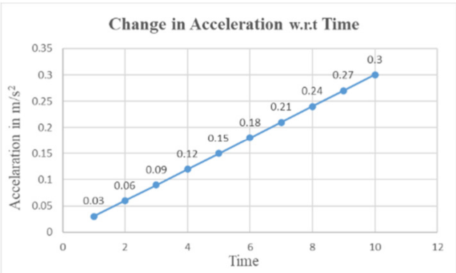


Fig. 8. Change in acceleration versus time.

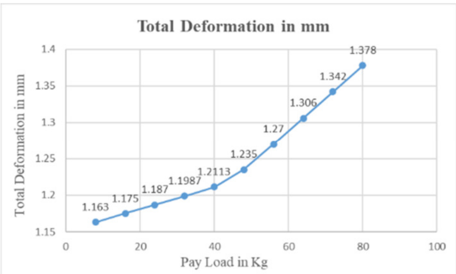


Fig. 9. Total deformation of the Caterbot. The labels show the value of total deformation corresponding to the payload.

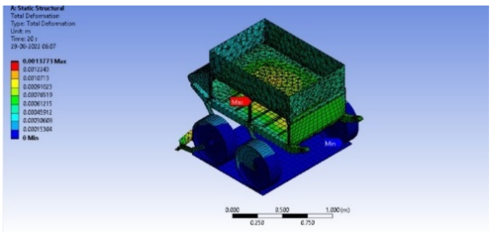


Fig. 10. Total deformation of Caterbot in ANSYS.

A. *Total Deformation*

Figure 9 shows the relationship between the total deformation in Caterbot and the applied payload. Total deformation is approximately directly proportional to the applied payload. As shown in Figure 10, the maximum value of the directional deformation along the y-axis is 1.1506 mm, which is at the center of the container of the Caterbot under the applied loading conditions.

B. *Directional Deformation*

Figure 11 shows the relationship between the directional deformation and the applied payload. It can be easily observed that the directional deformation is approximately directly proportional to the applied payload. When a payload of 80 kg was applied, the directional deformation was found to be 1.15 mm, which is permissible. The relationship between the value of the equivalent stress on the Caterbot and the applied payload is discussed. It can easily be observed that the equivalent stress is directly proportional to the applied payload, i.e., the value of maximum equivalent stress increases proportionally with the applied payload. Figure 13 shows the equivalent stress for Caterbot.

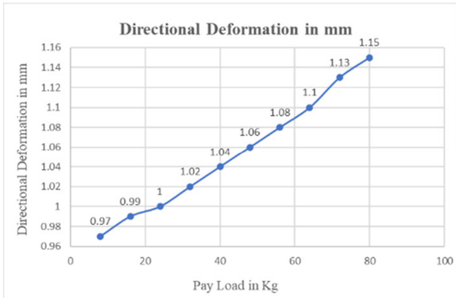


Fig. 11. Directional deformation for the Caterbot. The labels show the value of directional deformation corresponding to the payload.

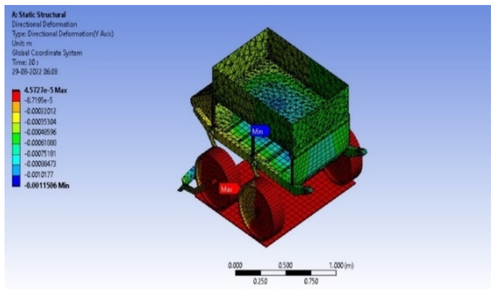


Fig. 12. Directional deformation of Caterbot in ANSYS.

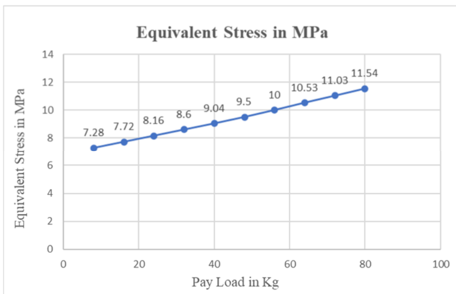


Fig. 13. Equivalent stress for Caterbot. The labels show the value of maximum equivalent stress corresponding to the payload.

C. Equivalent Elastic Strain

Figures 15 and 16 show the relationship between the equivalent elastic strain, applied payload, and other parameters. The strain increases proportionally with the payload. The structural analysis confirms that Caterbot remains within permissible strain limits under tested conditions, ensuring its safety and functionality for coconut harvesting. Overall, the ANSYS analysis offers insights into improving Caterbot's robustness and longevity in agricultural operations, contributing to advances in agricultural robotics for efficient coconut harvesting.

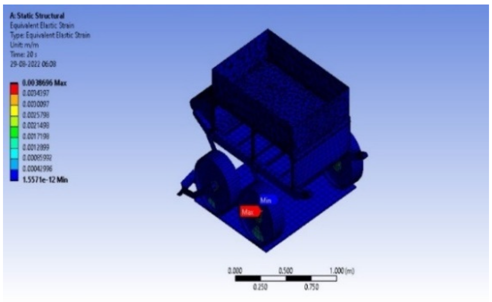


Fig. 14. Strain analysis of Caterbot in ANSYS.

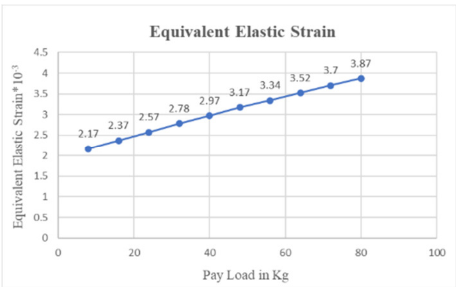
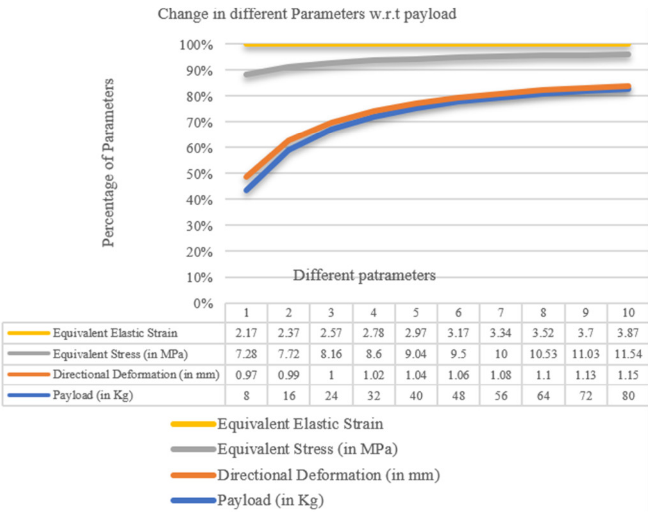


Fig. 15. Equivalent elastic strain for Caterbot. The labels show the value of equivalent elastic strain corresponding to the payload.



	1	2	3	4	5	6	7	8	9	10
Equivalent Elastic Strain	2.17	2.37	2.57	2.78	2.97	3.17	3.34	3.52	3.7	3.87
Equivalent Stress (in MPa)	7.28	7.72	8.16	8.6	9.04	9.5	10	10.53	11.03	11.54
Directional Deformation (in mm)	0.97	0.99	1	1.02	1.04	1.06	1.08	1.1	1.13	1.15
Payload (in Kg)	8	16	24	32	40	48	56	64	72	80

Fig. 16. Change in different parameters versus payload.

VI. CONCLUSION AND FUTURE SCOPE

The results confirm that Caterbot operates safely within the prescribed limits for strain, stress, and deformation, indicating its ability to efficiently transport the expected coconut volume. With its lightweight design, electric propulsion, and cost-effectiveness, Caterbot fulfills its development goals, promising efficient coconut harvesting operations when deployed as specified. The main calculation results highlight the maximum allowed strain and stress thresholds, providing crucial insights for improving their durability and efficiency in demanding agricultural environments. By addressing these factors, this study paves the way for the development of more robust and reliable agricultural robots, ultimately benefiting small and marginal farmers by reducing operational costs and enhancing productivity.

Project Caterbot initially focuses on creating an economically viable assistant tool for small and marginal farmers, beginning with coconut transport, and extending it to other crops. Future iterations will include features such as hydraulic unloading mechanisms, obstacle detection sensors, customizable builds, and additional agricultural functionalities, ultimately aiming to provide a versatile, cost-effective solution to address labor shortages and replace high-cost machinery in farming.

REFERENCES

[1] "Agriculture and allied industries industry report," India Brand Equity Foundation (IBEF). [Online]. Available: https://www.ibef.org/industry/agriculture-india.

[2] "Green Earth Research Network." https://www.gejournal.net/.

[3] "India at a glance | FAO in India | Food and Agriculture Organization of the United Nations." https://www.fao.org/india/fao-in-india/india-at-a-glance/en.

[4] P. A. Jithu, V. Prithviraj, and S. Patel, "Development and testing of a domestic coconut climber," B.S. Thesis, Department of Farm Power and Machinery, 2019.

[5] S. R. Kappil, R. Aneja, and P. Rani, "Decomposing the performance metrics of coconut cultivation in the South Indian States," *Humanities and Social Sciences Communications*, vol. 8, no. 1, pp. 1–8, May 2021, https://doi.org/10.1057/s41599-021-00783-0.

[6] R. Srinivasan, K. S. Anil Kumar, M. Chandrakala, K.V. Niranjana, N. Maddileti, and Rajendra Hegde, "Characterization and classification of major coconut growing soils in South Eastern Ghats of Tamil Nadu, India," *Journal of Plantation Crops*, vol. 49, no. 2, pp. 94–103, Sep. 2021, https://doi.org/10.25081/jpc.2021.v49.i2.7255.

[7] A. Deen *et al.*, "Chemical composition and health benefits of coconut oil: an overview," *Journal of the Science of Food and Agriculture*, vol. 101, no. 6, pp. 2182–2193, 2021, https://doi.org/10.1002/jsfa.10870.

[8] R. K. Megalingam, K. M. Sakthiprasad, M. M. Sreekanth, and G. V. Vivek, "A Survey on Robotic Coconut Tree Climbers – Existing Methods and Techniques," *IOP Conference Series: Materials Science and Engineering*, vol. 225, no. 1, Dec. 2017, Art. no. 012201, https://doi.org/10.1088/1757-899X/225/1/012201.

[9] M. Sadeghi and A. Moradi, "Design and Fabrication of a Column-Climber Robot (Koala Robot)," *International Journal of Aerospace and Mechanical Engineering*, vol. 2, no. 4, pp. 220–225, 2008.

[10] B. Sebastian, D. N. Ray, and S. Majumder, "Design and analysis of a tree climbing robot," in *Proceedings of the 2015 Conference on Advances In Robotics*, Goa, India, Apr. 2015, pp. 1–7, https://doi.org/10.1145/2783449.2783466.

[11] R. Aracil, R. Saltarén, and O. Reinoso, "Parallel robots for autonomous climbing along tubular structures," *Robotics and Autonomous Systems*,

vol. 42, no. 2, pp. 125–134, Feb. 2003, https://doi.org/10.1016/S0921-8890(02)00360-3.

[12] J. S. Amudhayazhini, P. Rajkumar, S. Ganapathy, and C. Indu Rani, "Studies on Engineering Properties of Coconuts for Effective Dehusking," *International Journal of Pure & Applied Bioscience*, vol. 7, no. 3, pp. 461–470, Jun. 2019, https://doi.org/10.18782/2320-7051.7520.

[13] A. Kumar, A. Pramanik, J. K. Singh, R. K. Tiwari, and S. Jena, "An ergonomic intervention for manual load carrying on Indian farms," *International Journal of Industrial Ergonomics*, vol. 83, May 2021, Art, no. 103126, https://doi.org/10.1016/j.ergon.2021.103126.

[14] J. H. Levin, "Using Wheels To Move Farm Loads," *USDA, Power to Produce*, pp. 45–51, 1960.

[15] S. R. Yadav, R. Kishor, N. Husain, and T. R. Singh, "Comparative economic analysis of tractor and bullock power use in crop production in district Sitapur (UP)," *Indian Journal of Agricultural Economics*, vol. 53, no. 3, 1998.

[16] F. Mocera, A. Somà, F. Mocera, and A. Somà, "A Review of Hybrid Electric Architectures in Construction, Handling and Agriculture Machines," in *New Perspectives on Electric Vehicles*, IntechOpen, 2021.

[17] A. Hassan, S. Z. Ilyas, A. Jalil, and Z. Ullah, "Monetization of the environmental damage caused by fossil fuels," *Environmental Science and Pollution Research*, vol. 28, no. 17, pp. 21204–21211, May 2021, https://doi.org/10.1007/s11356-020-12205-w.

[18] M. Bergerman, J. Billingsley, J. Reid, and E. van Henten, "Robotics in Agriculture and Forestry," in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Cham, Switzerland: Springer International Publishing, 2016, pp. 1463–1492.

[19] R. R. Shamshiri *et al.*, "Research and development in agricultural robotics: A perspective of digital farming," *International Journal of Agricultural and Biological Engineering*, vol. 11, no. 4, 2018, https://doi.org/10.25165/j.ijabe.20181104.4278.

[20] D. Ravi and P. Anand, "Production and Applications of Artificial seeds: A Review," *International Research Journal of Biological Sciences*, vol. 1, no. 5, pp. 74–78, 2012.

[21] H. L. Kushwaha *et al.*, "Status and Scope of Robotics in Agriculture," in *International Conference on Emerging Technologies in Agricultural and Food Engineering*, Dec. 2016, pp. 264–277.

[22] K. R. Aravind, P. Raja, and M. Pérez-Ruiz, "Task-based agricultural mobile robots in arable farming: A review," *Spanish Journal of Agricultural Research*, vol. 15, no. 1, Apr. 2017, Art. no. e02R01, https://doi.org/10.5424/sjar/2017151-9573.

[23] L. F. P. Oliveira, A. P. Moreira, and M. F. Silva, "Advances in Agriculture Robotics: A State-of-the-Art Review and Challenges Ahead," *Robotics*, vol. 10, no. 2, Jun. 2021, Art. no. 52, https://doi.org/10.3390/robotics10020052.

[24] L. Ding, H. Gao, Z. Deng, K. Nagatani, and K. Yoshida, "Experimental study and analysis on driving wheels' performance for planetary exploration rovers moving in deformable soil," *Journal of Terramechanics*, vol. 48, no. 1, pp. 27–45, Feb. 2011, https://doi.org/10.1016/j.jterra.2010.08.001.

[25] Y. Maddahi, N. Sepehri, A. Maddahi, and M. Abdolmohammadi, "Calibration of wheeled mobile robots with differential drive mechanisms: an experimental approach," *Robotica*, vol. 30, no. 6, pp. 1029–1039, Oct. 2012, https://doi.org/10.1017/S0263574711001329.

[26] Y. S. Polyakov, V. P. Gileta, and Y. V. Vanag, "Creation of the Drive of the Caterpillar Mover of a Wheel Vehicle," in *2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE)*, Novosibirsk, Russia, Oct. 2018, pp. 347–350, https://doi.org/10.1109/APEIE.2018.8545913.

[27] F. Rowlinson, "A New Caterpillar Development," *Scientific American*, vol. 126, no. 3, pp. 194–195, Mar. 1922, https://doi.org/10.1038/scientificamerican0322-194.

[28] D. Teng, "A Full Caterpillar Robotic Vehicle Design," in *2021 International Conference on Computer, Control and Robotics (ICCCR)*, Shanghai, China, Jan. 2021, pp. 156–160, https://doi.org/10.1109/ICCCR49711.2021.9349274.

[29] I. Leskovets and E. Melnikova, "Simulation Model of the Caterpillar Drive of the Tractor," *Machines. Technologies. Materials.*, vol. 8, no. 4, pp. 3–6, 2014.

[30] R. Y. Dobretsov, S. A. Voinash, S. N. Dolmatov, and P. G. Kolesnikov, "Pneumatic Caterpillar Mover for a Light Transport Vehicle," *IOP Conference Series: Earth and Environmental Science*, vol. 666, no. 4, Nov. 2021, Art. no. 042003, https://doi.org/10.1088/1755-1315/666/4/042003.

[31] J. J. Martins, M. Silva, and F. Santos, "Safety Standards for Collision Avoidance Systems in Agricultural Robots - A Review," in *ROBOT2022: Fifth Iberian Robotics Conference*, 2023, pp. 125–138, https://doi.org/10.1007/978-3-031-21065-5_11.

[32] G. R. Aby and S. F. Issa, "Safety of Automated Agricultural Machineries: A Systematic Literature Review," *Safety*, vol. 9, no. 1, Mar. 2023, Art. no. 13, https://doi.org/10.3390/safety9010013.