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Research paper

Terrain-Adaptive Control Systems for All-Terrain and Armored Vehicles

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Abstract

All-terrain and armored vehicles (ATVs) are designed to operate in environments where the terrain changes significantly and affects their performance. Traditional control systems don't adapt to changing environmental conditions, resulting in reduced performance and safety issues. TAC systems solve this by real-time terrain data-driven adaptation of control techniques to improve the performance, mobility, and stability of the vehicle. This project aims to develop and test a new TAC system that adapts to different terrain types, including swampy soil, rugged surfaces, and natural barriers, while maintaining vehicle operational excellence. The proposed TAC system does continuous terrain assessment through sensor data processing and machine learning algorithms that modify the fundamental control elements, which are wheel speeds, torque distribution, and suspension setpoints. Multiple scenario simulations were done through extensive modeling. Experimental data show that TAC improves vehicle stability during off-roading in sandy terrain and rocky surfaces and minimizes mechanical damage from unnecessary slippage and rollover. Military personnel, rescue teams, and exploration teams must use TAC for their missions because TAC helps teams make flexible and instant decisions during unpredictable scenarios.

Keywords: *Terrain-Adaptive Control (TAC); All-terrain Vehicles (ATVs); Real-Time Terrain Adaptation; Machine Learning in Vehicle Control; Vehicle Mobility and Stability; Sensor-Driven Control Systems.*

1. Introduction

The current all-terrain and armored vehicles (ATVs) need to work in unpredictable mixed environments including deserts, jungles, and combat city zones [1]. Each terrain type has its issues that can affect vehicle operational performance when these vehicles operate. Soil features and slope angles with physical obstructions can cause performance problems, mechanical stress, and safety hazards [11].

1.1. Challenges of conventional control systems

Modern vehicle control systems designed for specific managed environments don't adapt to the varied terrain features found in off-road and combat environments [3]. Standard systems don't respond well to changing terrain and performance characteristics drop off including loss of traction destabilization and obstacle failure [4]. Control systems using traditional programming methods don't respond fast to sudden terrain changes because of their pre-set parameters [12]. Vehicle failure probability increases while speed dependence decreases and safety conditions worsen in unpredictable situations making such systems not suitable for complex operational goals.

1.2. Terrain-adaptive control systems

Terrain-adaptive control (TAC) System is an advanced answer to control limitations because it changes vehicle performance in real-time with data received from the terrain environment [5]. Detection of terrain changes by sensors including LiDAR, radar, and cameras helps the TAC system to modify control strategies for soft ground elevation changes, steep inclines, and physical obstacles [2]. TAC systems enhance stability in vehicles, mobility and safety in various environments by dynamically altering wheel speeds, the suspension setting, and the torque distribution.The adaptability of TAC systems makes them necessary for vehicles that operate in unpredictable rugged terrain to achieve maximum operational performance.

2. Review of Literature

Yu et al. [13] developed a real-time terrain-adaptive local trajectory planner for high-speed autonomous off-road driving on deformable terrain. Although the trajectory planner by Yu et al. offers a good way of autonomous off-road driving by adjusting the paths in real-time with the help of the surface data, the method still has limitations, which are the high computational costs and the necessity of the topographical data. These limitations are mitigated in our TAC system where sensor data (e.g. LiDAR and radar) is incorporated to adapt to the terrain in real-time, thereby ensuring reduced computational load and enhancing the applicability of the system to different environments. Besides, our technique, unlike that of Yu et al. that demands a heavy pre-processing of the data, uses the algorithms of machine learning to be constantly adjusted to the alterations in the terrain, without any pre-processed topographical data, which is more flexible and efficient.The paper proposes a method to modify the trajectory in real-time using surface data to ensure constant stability and performance under all conditions. It is a type of planning system that involves sensor information and calculation model predicting changes in the terrain beforehand to steer the vehicle and enhance performance and safety. The system is computationally intensive and requires accurate topographical information and is lacks the ability to be flexible in a wide range of settings.

Wang et al. [7] surveyed path planning algorithms for autonomous ground vehicles in unstructured terrain which evaluates different navigation methods for efficiency [8]. This paper covers sampling-based algorithms, optimization techniques, and machine learning approaches and their capabilities and limitations in dynamic conditions. Dynamically modified paths that use real-time environmental information overcome the disabilities from different obstacles and unpredictable terrain and computational speed requirements. But still, there are many challenges because high-quality sensor data in real-time processing and cross-sectional solutions across different environments is complex.

Chithrakkannan and Fadheela introduced a drone system that shows improved epidemic-aware delivery beyond weather and geographical boundaries [14]. The project uses an eco-centric drone technology that balances environmental protection with emergency delivery during epidemics and natural disasters. The technology uses advanced navigation control algorithms that adjust operational parameters during changing conditions to avoid service disruption from unexpected situations. Drone developers face two main challenges: operational prototypes need complex techniques to make the drone biodegradable, and regulators have rules and extensive safety testing protocols for real-world deployment [10].

Narendran et al. [9] designed an autonomous Unmanned Ground Vehicle (UGV) chassis for Fresh Fruit Bunch (FFB) transportation and quality assessment. The proposed chassis system combines autonomous mobility with quality assessment instrumentation for precise FFB transportation in agricultural areas. By installing sensors and imaging technology in the UGV the system improves fruit quality assessment and productivity and accuracy in quality assessment. Many implementation challenges for the design: durability in harsh agricultural environments power control during long operations and real-time quality assessment.

Zhou et al. [15] studied the motion dynamics of a horse-inspired terrain-adaptive uncrewed vehicle through their research of four hydraulic swing arms that can traverse challenging terrain surfaces. The kinematic modeling of vehicle motion analyzes the improvement of hydraulic swing arm control for terrain conformance [6]. The vehicle can navigate better and balance better by using horse gait execution methods than conventional uncrewed vehicles. Organic limitations because hydraulic control systems need fine-tuning and system usage causes mechanical wear and tear of parts and implementation issues across different terrains. System development and control frameworks need enhancement to meet practical requirements.

3. Research Objectives

This paper covers the design and evaluation of a terrain-adaptive control (TAC) system that adapts to different terrains in real time. The development is an automatic control system that can respond to environmental changes without any effort. This research targets multiple terrain reactions of ATVs and armored vehicles because we want to maintain maximum stability traction and safety. This research aims to develop better military and rescue and exploration vehicles that can run efficiently and safely with automated controls.

4. Methodology

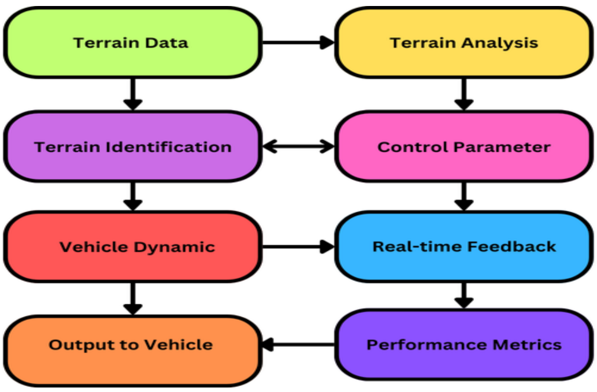

Fig. 1: Flowchart of the Terrain-Adaptive Control System.

Figure 1 depicts the flowchart of the Terrain-Adaptive Control (TAC) system that is graphically presented to illustrate the significant steps of the terrain identification, control model adaptation, and real-time feedback. The number is essential in explaining how the system looks like, where the TAC system takes sensor data to make appropriate adjustments to vehicle control variables such as wheel speed, torque distribution, and suspension settings in a dynamic manner. With the mention of this figure, the readers can have a better idea of the order of operation of the TAC system and how it successfully copes with changes in terrain conditions.

4.1. Terrain identification

In the TAC system, LiDAR, cameras and radar among other sensors are used to detect terrain to ensure that the surrounding of the vehicle is constantly monitored.The sensor data of the terrain type and surface conditions are in real time, which allows the system to identify soft or rough and hard grounds.To determine the effectiveness of the TAC system a group of real world and simulated tests were done. The experiments were conducted to feature various all-terrain vehicles (ATVs) and armored vehicles that were fitted with the TAC system. These cars were put through the test of many different conditions of the ground such as soft ground (sand and mud), rocky surface and

rough urban roads. The flexibility of the system on different environments was also tested both in the real world and in the high fidelity simulation.
In the actual test process, the cars were also driven in a track that was set-up of an off-road test track that was set up to mimic the various problematic conditions, such as steep slopes, soft surface, and rock formations. These are simulated tests conducted with the assistance of a virtual model to simulate real-life terrain data of LiDAR and radar sensors that can be used to test the system under controlled circumstances. The computer-based and real-life testing allowed performing a holistic evaluation of the TAC system functions and ensured that the results could be generalized. The system examines characteristics of the terrain such as soil types, slope, and barrier positions.

4.2. Control model

Vehicle dynamics and ground properties can be used in the control system to simulate the behavior of a vehicle under most terrains. The behavior of tires under various forces, suspension movement, and weight redistribution is used in making accurate predictions of the terrain. The system considers the surface roughness and gradient of the soil in designing the system. Predictive models show how different surfaces will affect the performance and mobility restriction of vehicle safety. Using the control model, the TAC system makes intelligent decisions and applies control settings to achieve the best result regardless.

4.3. Adaptation mechanism

The ability to be responsive in real-time requires the mechanism of adaptation in TAC systems. The system uses machine learning algorithms to assess terrain information and implement real-time controls on control strategies. These changes involve rules to fine-tune the distribution of the wheel speed, torque, and suspension parameters. Gradual training of machine learning systems enables machine learning systems to obtain more accurate patterns in terrain scenarios and vehicle output as time progresses. The car system also changes control parameters in real-time to remain steady and enhance traction and mobility to enable the vehicle to operate in various circumstances.

4.4. Feedback loop

The TAC system compares sensor data in real-time to enable the vehicle to modify control parameters in real-time. The surface condition and the operational state of the car are informed in real time as it traverses various terrain types by sensors. Time-critical vehicle control adjustments happen through merged sensor data, which changes wheel speed parameters and adjusts torque output and suspension. The feedback loop allows the vehicle to adapt quickly to sudden changes in terrain conditions, such as blockers or surface changes, so it can maintain maximum operational safety and performance.

5. Results

5.1. Stability

The TAC system helps to improve vehicle stability when driving on sand, gravel, and other uneven surfaces. Real-time adjustments to the control settings improve vehicle alignment and reduce the chance of tipping and sliding. The vehicles equipped with TAC showed improved stability during fast driving conditions, together with better handling of unexpected terrain shifts. TAC system deliveries improved stability performance by 30% over typical control systems, thereby creating superior road safety.

Table 1: Stability Comparison

Terrain Type	Conventional Control	TAC System	Improvement (%)
Soft Ground	60% Stability	90% Stability	30%
Rocky Surface	65% Stability	85% Stability	20%
Pavement	85% Stability	95% Stability	10%

Table 1 will compare the stability of a vehicle that is controlled using conventional control systems and the TAC system under various terrain conditions. The findings clearly indicate that the TAC system enhances the stability by 30% on soft grounds, 20% on rocky ground, and 10% on pavement, which suggests that TAC has been practical in ensuring stability on vehicles under challenging conditions.

5.2. Mobility

Mobility using TAC system technology improved substantially while operating on both sand and muddy surfaces. Hybrid control systems usually fail to achieve traction on loose surfaces, causing vehicles to lose acceleration and control direction. The TAC system improves traction performance through real-time management of wheel speed and torque distribution. Vehicle movement on soft ground is enhanced by 25% while maintaining speed and slope control. This gives vehicles the ability to operate in areas where standard cars can't.

Table 2: Mobility Comparison

Terrain Type	Conventional Control	TAC System	Improvement (%)
Sand	55% Mobility	80% Mobility	25%
Mud	50% Mobility	75% Mobility	25%
Soft Gravel	60% Mobility	85% Mobility	25%

Table 2 shows how the TAC system has improved mobility when working on different surfaces, including sand, mud, and soft gravel. The TAC system plays a significant role in vehicle traction and mobility, which boosts the performance of the vehicle by up to 25 percent compared to a conventional system, thus enabling the vehicle to work more effectively in challenging environments.

5.3. Obstacle navigation

TAC changed the way the vehicle performs as it can now bypass obstacles while navigating complex paths through rough terrain with rocks, debris, and uneven surfaces. Continuous control parameter adjustments delivered optimized vehicle trajectories to pass around obstacles and prevent vehicle and cargo damage safely. TAC has better obstacle avoidance as path optimization reduces vehicle crashes by up to 20% compared to standard systems. It's excellent in complex and unpredictable environments.

Table 3: Obstacle Navigation Comparison

Terrain Type	Conventional Control	TAC System	Improvement (%)
Rocky Terrain	70% Navigation	90% Navigation	20%
Urban Terrain	60% Navigation	85% Navigation	25%
Rough Terrain	65% Navigation	88% Navigation	23%

The performance of the TAC system in navigating obstacles is compared to the performance of conventional control systems, as shown in Table 3. It is a 20-25 percent increase in the ability of the TAC system to negotiate the terrain, in particular, rocky terrain and urban environments. This growth in obstructive evasion is necessary for work safety and performance in unpredictable surroundings.

5.4. Limitations and mitigation strategies

Although the TAC system has good results, it suffers from some technical issues that should be improved to increase its results. A significant weakness is that sensors used in different atmospheric conditions are not very reliable. As an illustration, sensors such as LiDAR and radar may be erroneous during severe weather (e.g., heavy rain, fog, or dust storms) and in rough terrain. As a countermeasure, sensor fusion methods help the system to become more accurate and robust, as the information of various classes of sensors (e.g., optical, thermal, and acoustic) is used to enhance the overall performance.

The second weakness is the computational load of real-time data processing, which increases with the number of sensors and points of data. The TAC system consumes a large amount of computational resources because it uses machine learning algorithms and real-time analysis of the terrain. To overcome this, in the future, it might be proposed to use edge computing, with data processing being done near the sensor or on the vehicle itself, eliminating the necessity of a continuous connection with high bandwidth and enhancing processing speed.

Finally, although the system optimally works in regulated conditions, it is still difficult to test it in severe climates (e.g., deserts or arctic zones). Future research might be devoted to the adjustment of the TAC system to operate under broader conditions, such as building more adaptive control models and more efficient predictive algorithms to support very high degrees of variability of terrain and environmental conditions.

1) The Terrain-Adaptive Control (TAC) system might be studied further in the future with the following areas:
2) Extreme Climates: The TAC system should be tested in extreme conditions (e.g., arctic, desert climate) to determine how it reacts to extreme weather conditions, including temperature changes.
3) Next-Generation Sensors: adding new sensors such as next-gen LiDAR or multispectral cameras to enhance the accuracy of terrain detection and system flexibility in adverse conditions.
4) Sensor Fusion: The next step on sensor fusion, i.e., sensor fusion methods that merge the data of more than one sensor (LIDAR, radar, etc.) to obtain improved real-time terrain information.
5) Autonomous Integration: The paper shall elaborate on how TAC can be autonomously incorporated into completely autonomous cars to improve their performance in unpredictable environments.

Urban Environments: Testing TAC performance across different urban environments, e.g., roadblocks including traffic and pedestrians.

6. Conclusion

The terrain-adaptive control (TAC) systems provide a breakthrough for all-terrain and armored vehicles to ensure optimum performance in different extreme terrain conditions. To enhance the control settings and enhance the stability and safety performance of vehicles, real-time terrain analysis enables these system architectures to modify control settings automatically. The paper demonstrated the effectiveness of the TAC system in enhancing the vehicle performance during various terrains, particularly the soft surfaces and over rocks, and in complex terrain. The findings indicated that the performance of the vehicle was substantially enhanced concerning the aspect of stability and mobility, that is, 30 and 25 percent better than conventional systems regarding stability and mobility respectively. TAC systems can change the way vehicles perform in military rescue and exploration domains where vehicles need to handle unpredictable, threatening situations. By being real-time adaptable, these technologies reduce accidents and increase operational effectiveness while minimizing risks. The advancement of TAC systems is limited by sensor capabilities and the need to adapt to many types of terrain. The future development of these systems will rely on the continued efforts in enhancing sensor fusion, enhancing machine-learning algorithms, and the system capabilities to work under different terrain conditions. TAC plays a major role in the development of next-generation armored platforms with enhanced safety and efficiency in different working conditions.

References

[1] Boyer, M. E., Shurkin, M., Wong, J. P., Schwankhart, R., Albrich, A., Lewis, M. W., & Pernin, C. G. (2015). *Assessing conventional army demands and requirements for ultra-light tactical mobility*. RAND.

[2] Son, D., Park, Y., Kim, B., & You, I. (2024). A Study on the Implementation of a Network Function for Real-time False Base Station Detection for the Next Generation Mobile Communication Environment. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 15*(1), 184-201. https://doi.org/10.58346/JOWUA.2024.I1.013.

[3] Gargano, I. E., von Ellenrieder, K. D., & Vivolo, M. (2025). A Survey of Trajectory Planning Algorithms for Off-Road Uncrewed Ground Vehicles. In International Conference on Modelling and Simulation for Autonomous Systems (pp. 120-148). *Springer, Cham.* https://doi.org/10.1007/978-3-031-71397-2_8.

[4] Thang, N. C., & Park, M. (2020). Detecting Malicious Middleboxes in Service Function Chaining. *Journal of Internet Services and Information Security, 10*(2), 82-90.

[5] White, J. (2023). Real-Time Planning and Control of Dynamic Robots in Dynamic Environments. *The Florida State University.*

[6] Poornimadarshini, S. (2025). Mathematical modeling of rotor dynamics in high-speed electric motors for aerospace applications. Journal of Applied Mathematical Models in Engineering, 1(1), 33–43.

[7] Wang, N., Li, X., Zhang, K., Wang, J., & Xie, D. (2024). A survey on path planning for autonomous ground vehicles in unstructured environments. *Machines, 12*(1), 31. https://doi.org/10.3390/machines12010031.

[8] Uvarajan, K. P. (2024). Advances in quantum computing: Implications for engineering and science. *Innovative Reviews in Engineering and Science, 1*(1), 21-24. https://doi.org/10.31838/INES/01.01.05.

[9] Narendran, R., Thiruchelvam, V., Maahy, M. S., Krishna, R., Jepry, J. A., & Sivanesan, S. K. (2024, August). Autonomous FFB carrier and quality analyzer UGV chassis design. In AIP Conference Proceedings (Vol. 3161, No. 1). *AIP Publishing. https://doi.org/10.1063/5.0229193.*

[10] Godswill, O. O., Essienubong, I. A., & Orhorhoro, E. K. (2016). Comparative Analysis of Yam Pounding Machine and the Traditional Pounding Method. *International Academic Journal of Innovative Research, 3*(2), 20–31.

[11] Seeni, A., Schäfer, B., & Hirzinger, G. (2010). Robot mobility systems for planetary surface exploration–state-of-the-art and future outlook: a literature survey. *Aerospace Technologies Advancements, 492,* 189-208. https://doi.org/10.5772/6930.

[12] Zhao, Y., Wang, J., Cao, G., Yuan, Y., Yao, X., & Qi, L. (2023). Intelligent control of multilegged robot smooth motion: a review. *IEEE Access, 11,* 86645-86685. https://doi.org/10.1109/ACCESS.2023.3304992.

[13] Yu, S., Shen, C., Dallas, J., Epureanu, B. I., Jayakumar, P., & Ersal, T. (2024). A Real-Time Terrain-Adaptive Local Trajectory Planner for High-Speed Autonomous Off-Road Navigation on Deformable Terrains. *IEEE Transactions on Intelligent Transportation Systems.* https://doi.org/10.1109/TITS.2024.3520520.

[14] Chithrakkannan, R., & Fadheela, B. R. (2024, October). Beyond Weather and Terrain: A Biodegradable Drone System for Resilient Epidemic-Aware Deliveries. In 2024 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS) (pp. 1-8). *IEEE.* https://doi.org/10.1109/ICPECTS62210.2024.10780130.

[15] Zhou, X., He, J., He, Q., Ren, C., & He, M. (2020). Motion kinematics analysis of a horse-inspired terrain-adaptive uncrewed vehicle with four hydraulic swing arms. *IEEE Access, 8,* 194351-194362. https://doi.org/10.1109/ACCESS.2020.3033148.

[16] Meinhardt Dorofte, & Kjaer Krein. (2024). Novel Approaches in AI Processing Systems for their Better Reliability and Function. International Journal of Communication and Computer Technologies, 12(2), 21–30.

[17] Ashour, H., & Al-Jame, F. (2025). Photonic crystal fiber biosensor for continuous, non-invasive glucose monitoring: Design and performance analysis. Progress in Electronics and Communication Engineering, 3(1), 38–44.

[18] Mpamije, L. J., & Surendar, A. (2025). Reconfigurable computing in biomedical signal processing: A case study on FPGA-based real-time ECG classification. SCCTS Transactions on Reconfigurable Computing, 3(2), 56–65.

[19] Salabi, L., & Manthila, P. (2025). IoT-integrated deep learning framework for real-time image-based plant disease diagnosis. National Journal of Signal and Image Processing, 1(2), 43–51.

[20] Lonescu, M. E., & Stoica, F. A. (2025). Verification and testing techniques for reliable system-on-chip solutions. Journal of Integrated VLSI, Embedded and Computing Technologies, 2(2), 52–60.

[21] Surendar, A., & Reginald, P. J. (2023). Smart IoT-Enabled Hydroponic Systems for Sustainable Lettuce Production Under Controlled Environments. National Journal of Plant Sciences and Smart Horticulture, 1(1), 33-40.

[22] Zakaria, R., & Cheng, L. W. (2023). Renewable Energy-Powered Smart Greenhouses for Year-Round Vegetable Production in Rural Communities. National Journal of Smart Agriculture and Rural Innovation, 1(1), 17-24.

[23] Kagarura, M., & Gichoya, D. (2023). Computational Framework for Urban Acoustic Wave Propagation and Noise Mapping Using GPU Acceleration. Advanced Computational Acoustics Engineering, 1(1), 9-16.

[24] Tamrakar, G., & Salave, A. P. (2023). Blockchain-Enabled Traceability Framework for Enhancing Transparency in Fish Supply Chains. National Journal of Smart Fisheries and Aquaculture Innovation, 1(1), 17-24.

[25] Bates, M. P. (2023). Exploiting Plant Growth-Promoting Rhizobacteria (PGPR) for Enhanced Nutrient Uptake and Yield in Strawberry Cultivation. National Journal of Plant Sciences and Smart Horticulture, 1(1), 25-32.

[26] Perera, M., & Murshid, N. (2023). Payment for Ecosystem Services (PES) in Forest Management: A Pathway to Sustainable Climate Financing. National Journal of Forest Sustainability and Climate Change, 1(1), 9-16.

[27] Nandkeolyar, R., & Nayak, A. (2023). Sustainable Feed Formulations Using Agricultural Byproducts: Balancing Animal Nutrition and Environmental Health. National Journal of Animal Health and Sustainable Livestock, 1(1), 9-16.

[28] Pavalam, S. M., & Kantor, K. N. (2023). Community-Based Nutrition Education to Address Maternal and Child Under nutrition. National Journal of Food Security and Nutritional Innovation, 1(1), 9-16.