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Enhanced Ground Traversability Estimation for Quadruped Robots using Improved CNN Architectures and Expanded Heightmap Dataset

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Abstract:

Traversability estimation is a key prerequisite for safe and efficient navigation of quadruped robots in unstructured environments. While previous research demonstrated the use of convolutional neural networks (CNNs) for classifying terrain heightmap patches into traversable and non-traversable categories, limitations in dataset size and shallow network architecture restricted model generalization. In this paper, we extend prior work by (i) expanding the simulated dataset from 12 to 60 diverse heightmaps and (ii) improving the CNN architecture by introducing deeper convolutional layers, batch normalization, dropout regularization, and the Adam optimizer. These modifications increased classification accuracy from 82% to 96%, significantly enhancing robustness across diverse terrain conditions. The proposed model is integrated into a traversability-aware path planning framework, enabling quadruped robots to select safer and smoother trajectories in complex terrains. Unlike handcrafted geometric features, the CNN-based method learns to extract relevant spatial patterns automatically. The increased dataset diversity not only improves classification accuracy but also ensures robustness across different terrain morphologies, including hills, slopes, rocky surfaces, and uneven patches. This work thus bridges the gap between limited simulation-based traversability studies and real-world deployment challenges.

Keywords: CNN, quadruped robots, traversability estimation, deep learning, path planning, Gazebo simulation

Introduction:

Navigation in unstructured terrains requires reliable traversability estimation to prevent robots from becoming immobilized in rough, obstacle-rich, or irregular regions. Natural environments such as rocky hillsides, collapsed structures, or crater-like depressions often present unpredictable conditions where small errors in terrain assessment can result in significant instability. Earlier methods based on slope thresholds, terrain roughness indices, or geometric heuristics often fail in these environments, as they cannot capture the complexity and variability of natural terrain features (Balta et al., 2013; Silver et al., 2010).

To overcome these limitations, recent research has leveraged convolutional neural networks (CNNs) applied to heightmaps, where local image patches are labeled as traversable or non-traversable based on robot simulation outcomes (Chavez-Garcia et al., 2017; Giusti et al., 2016). CNNs provide the advantage of learning hierarchical spatial features directly from data, reducing reliance on manually engineered features. However, prior approaches faced two major challenges: (i) dataset limitations—most studies used only

12 terrains, which provided insufficient variability for robust generalization (Dhande & Ohol, 2022), and (ii) architectural limitations—shallow CNNs with only a small number of filters per convolutional layer (e.g., 5) lacked the representational power required to distinguish subtle terrain differences. These limitations led to suboptimal accuracy of around 82% and poor adaptability to unseen terrains.

In this paper, we address these challenges with two main contributions:

Dataset Expansion. We created 60 diverse custom terrains in simulation, resulting in a significantly larger and richer dataset that captures a wider range of terrain morphologies (Fankhauser et al., 2018).

Improved CNN Architecture. We designed a deeper CNN model with increasing filter sizes (32–64–128) across layers, combined with batch normalization, dropout regularization, and the Adam optimizer (Kingma & Ba, 2015). This architecture achieved a classification accuracy of 96%.

Reliable traversability estimation is not only valuable for simulation studies but is also critical for real-world robotic applications such as planetary exploration rovers, autonomous military systems, and search-and-rescue operations in hazardous environments (Cunningham et al., 2013; Gladisch et al., 2025). Quadruped robots, compared to wheeled or tracked robots, provide superior mobility in uneven and irregular terrains, but their higher degrees of freedom make them more vulnerable to instability when traversability predictions are inaccurate (Wellhausen et al., 2020).

Related Work:

Earlier traversability estimation methods primarily relied on slope thresholds, roughness indices, and geometric analysis to classify terrain (Balta et al., 2013; Zhou et al., 2022). While computationally simple, they often struggled in natural environments with irregular rocks, steep inclines, or mixed obstacle distributions. These handcrafted methods were sensitive to noise, environment-specific assumptions, and sensor inaccuracies, limiting scalability.

More recent CNN-based methods demonstrated that learning discriminative features directly from heightmaps can significantly outperform geometric heuristics (Chavez-Garcia et al., 2017; Shen et al., 2025). However, dataset richness and network depth remain critical for performance (Bansod et al., 2025). Our work extends these studies by enlarging the dataset from 12 terrains (Dhande & Ohol, 2022) to 60 and redesigning the CNN with deeper layers, batch normalization, and dropout, thereby improving generalization (Costa et al., 2025).In addition, reinforcement learning (RL) approaches have been applied to terrain-aware locomotion (Qureshi & Ayaz, 2014), but RL requires extensive simulation and faces a “reality gap” when transferred to physical robots (Zhang et al., 2024). In contrast, our supervised learning approach provides efficient, interpretable, and transferable terrain classification suitable for integration into higher-level planning (Fankhauser et al., 2016).

Approach:

A. Dataset Generation:

We simulated an Anymal quadruped robot in Gazebo and created 60 custom terrains (heightmaps), (similar to Fankhauser et al., 2018).compared to only 12 in prior work. The robot was commanded with constant velocity across these terrains. If the robot traversed the predefined threshold distance, the corresponding patches were labeled traversable; otherwise, non-traversable. This generated approximately

350,000 labeled patches at 20 Hz sampling rate. The terrains included synthetic hills, stair- like structures, random noise-based surfaces, and obstacle- rich maps. By increasing the variety of terrains, the dataset covers a wide spectrum of difficulty levels, ensuring that the model learns features beyond simple slopes. Additionally, each patch was normalized and resized before being fed into the CNN, ensuring consistency in training.

Fig.1. Custom Height Maps

The figure below shows the simulation of the Anymal quadruped robot across different terrains. These simulations illustrate the dataset creation process, where terrain patches were labeled as traversable or non-traversable based on the robot's interaction with the environment.

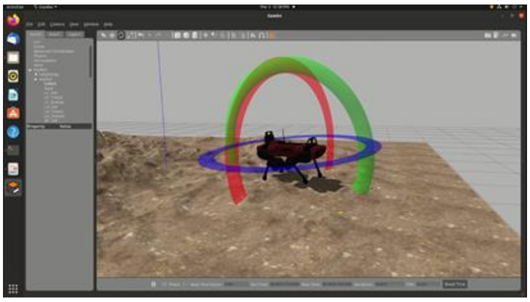

Fig. 2. Terrain 1

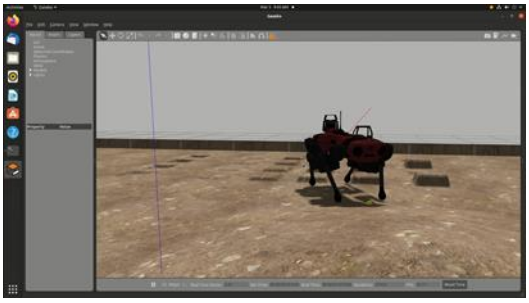

Fig. 3. Terrain 2

B. Baseline CNN

The baseline model consisted of three convolutional layers with 5 filters each (3×3 kernels), followed by max pooling and two dense layers (128 neurons and 2 output neurons). The model was trained using Adadelta optimizer and achieved 82 (Dhande & Ohol 2022)

C. Improved CNN (Proposed)

Our proposed CNN introduces the following improvements:

- Convolutional filters increased to 32, 64, and 128 in successive layers.
- Batch normalization applied after each convolutional block.
- MaxPooling layers for spatial down sampling.
- Fully connected layer with 128 neurons, followed by Dropout (0.5) to prevent overfitting.
- Final dense layer with 2 neurons and SoftMax activation.
- Adam optimizer used instead of Adadelta. (Kingma & Ba, 2015)

This modification significantly boosted performance, achieving a classification accuracy of 96%, which represents a substantial improvement over the baseline design. The progressive increase in convolutional filters (32 → 64 → 128) allows the network to first capture fine-grained local structures such as edges, slopes, or small irregularities, and then progressively abstract higher-level terrain characteristics like obstacles, hills, or uneven regions. This hierarchical feature extraction is essential for complex terrain understanding. Batch normalization further stabilizes the learning process by reducing internal covariate shift and maintaining consistent activation distributions across layers, thereby enabling faster and more reliable training. In addition, the inclusion of dropout regularization prevents excessive co-adaptation of neurons, forcing the network to learn more robust representations that generalize better to unseen terrains. Finally, the adoption of the Adam optimizer, instead of traditional methods such as Adadelta or stochastic gradient descent, provides adaptive learning rates that dynamically adjust for each parameter, significantly improving convergence speed while avoiding local minima. Together, these architectural and optimization refinements create a model that is not only more accurate but also more stable, efficient, and suitable for deployment in safety-critical robotic applications.

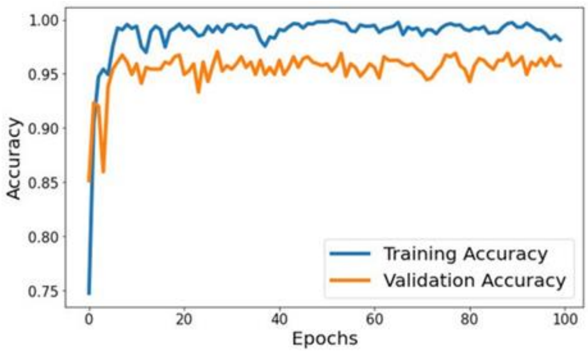

Fig 4. Accuracy Graph

D. Integration with DWA

As in the previous work, the classifier output is integrated into the cost function of the Dynamic Window Approach (DWA). With the improved classifier confidence, the algorithm selects smoother and more reliable trajectories, further reducing the likelihood of the robot entering non-traversable regions. (Dhande & Ohol, 2022),

Result:

The improved CNN demonstrated a 14% accuracy gain over the baseline model. Dataset expansion with 60 terrains further enhanced robustness and generalization, while Adam optimizer reduced training time compared to Adadelta. In addition, qualitative results from visual inspection of classification maps confirmed that the improved CNN was able to better distinguish subtle terrain variations that the baseline model often misclassified. The reduced training time highlights the efficiency of the Adam optimizer, which dynamically adjusts learning rates. Furthermore, the confusion matrix indicated that false positives (classifying non- traversable patches as traversable) were reduced significantly, which is critical for real-world robotic deployment where safety margins are essential. (Wellhausen et al., 2020).

Model	Dataset Size	Filters	Optimizer	Accuracy
Baseline CNN	12 heightmaps	5-5-5	Adadelta	82%
Proposed CNN (This Work)	60 heightmaps	32-64-128	Adam	96%

Conclusion and Future Work:

This study presented an enhanced CNN-based traversability estimation framework for quadruped robots. By expanding the dataset from 12 to 60 terrains and adopting a deeper CNN architecture with batch normalization, dropout, and the Adam optimizer, the proposed method improved accuracy from 82% to 96%. These results underline the importance of both dataset diversity and deeper networks for reliable terrain classification. The reduction in false positives and shorter training times further validate the model's practicality in robotic applications where both safety and efficiency are critical.

Beyond these direct accuracy improvements, this work contributes more broadly to the long-term vision of enabling quadruped robots to operate autonomously in highly variable and uncertain terrains. Reliable traversability estimation is a cornerstone capability for such robots, as it directly affects mission success in domains such as planetary exploration, underground mining, agricultural automation, and disaster response. The ability to correctly identify safe paths not only ensures operational continuity but also reduces maintenance costs and the risk of mission-critical failures.

Future research can extend this work in several promising directions:

1) Real-time generation of heightmaps from onboard sensors without relying solely on pre-simulated environments.
2) Deployment and validation on real quadruped hard- ware.
3) Incorporating multi-modal sensor fusion (LiDAR + camera) for further robustness.
4) Leveraging large-scale image datasets for pretraining, followed by fine-tuning on terrain data, may significantly reduce data requirements while improving generalization. Semi-supervised techniques could further help in scenarios with limited labeled terrain data.
5) Merging traversability estimation with reinforcement learning locomotion strategies would enable robots not just to classify terrain but also to adapt their gaits dynamically based on terrain difficulty.
6) Developing interpretable CNN models that provide explanations for their predictions will increase trust-worthiness, especially in safety-critical deployments.

Ultimately, this research envisions the deployment of intelligent quadruped robots capable of reliable, adaptive, and safe navigation in unstructured real-world environments. Such systems could play a transformative role in society, assisting in disaster recovery operations, enabling sustainable agricultural practices, conducting hazardous inspections in mines, and advancing planetary colonization missions. With continued improvements, the proposed framework serves as a stepping stone toward bridging the gap between controlled simulations and the demanding requirements of fully autonomous quadruped navigation in the real world.

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