Ground-based Detection of Martian Dust Devils With a Fine-tuned Fast R-CNN

Kacy Hatfield*, Conor A. Nixon, John Santerre, Ralph Lorenz

NASA Goddard Space Flight Center

***Correspondence**: kacy.hatfield@nasa.gov

Background: Martian Dust Devils

- **Planetary Prevalence:** Dust devils are far more prevalent on Mars than Earth, playing a significant role in the planet's atmospheric dust cycle and surface-atmosphere interactions [1].
- **Size Disparity:** Martian dust devils greatly exceed their terrestrial counterparts in scale, with the largest observed reaching a height of 20000 meters compared to Earth's maximum of 2500 meters [2].
- **Atmospheric Contribution:** These vortices contribute substantially to the Martian dust budget, mobilizing significant quantities of surface material into the atmosphere.
- **Climate Influence:** Dust devils impact surface albedo, atmospheric opacity, and thermal dynamics on Mars, making them central to understanding and modeling the Martian climate system [3].

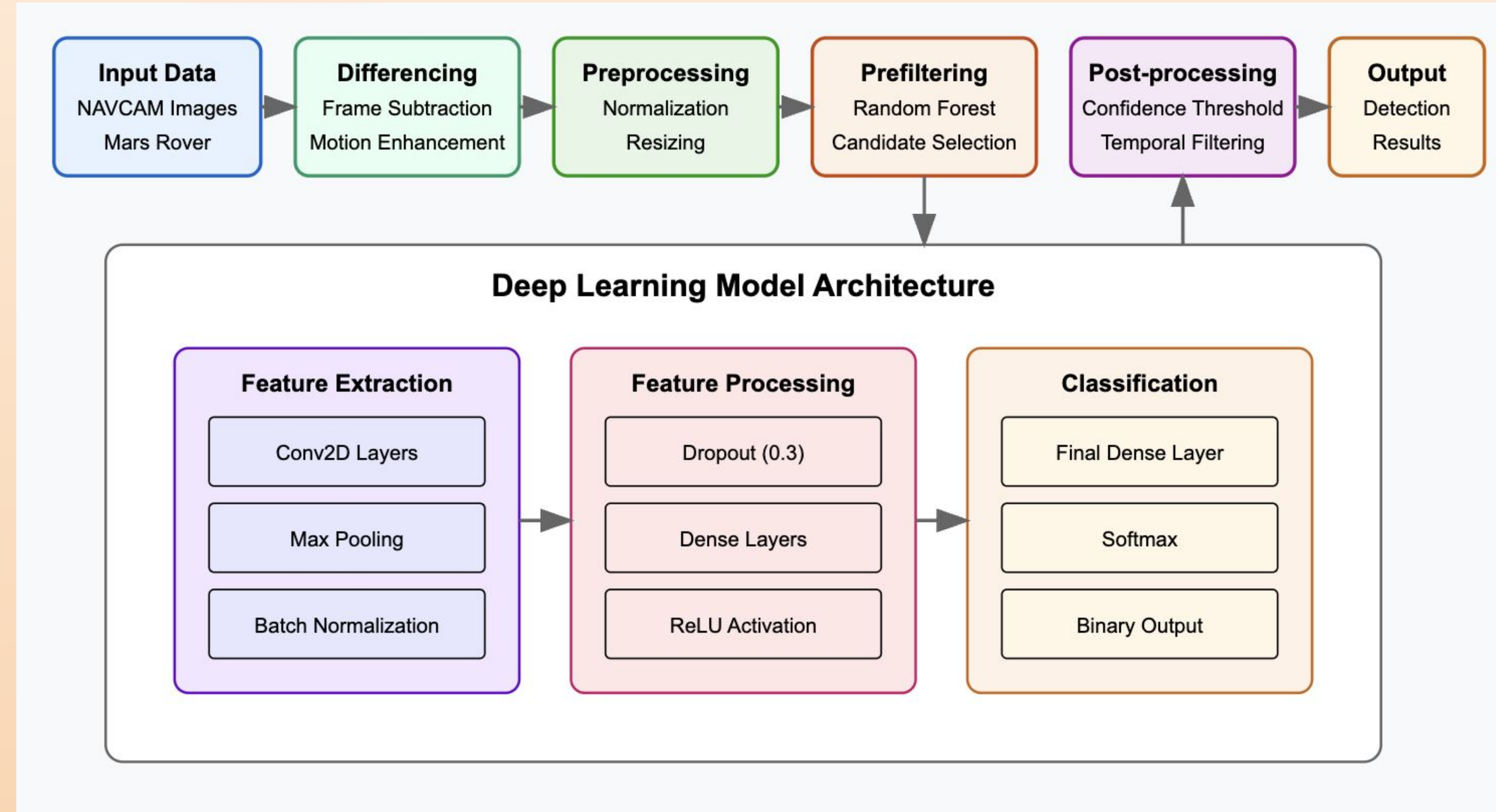
Sol 4332, Opportunity Rover, NavCam (NASA / JPL-Caltech)

Motivation: Deep Learning for Dust Devil Detection

Transformative Detection Paradigm: Our Faster R-CNN implementation revolutionizes the identification of elusive Martian dust devils, enabling automated analysis of these atmospheric phenomena that traditional methods frequently miss. This approach overcomes the significant challenge of manually processing hundreds of thousands of images where compression artifacts often obscure critical features. To this end, we investigated image data from the Navigation Cameras on rovers Spirit, Opportunity, Perseverance, and Curiosity.

- **Addressing Unique Morphological Challenges:** Martian dust devils present distinctive detection obstacles due to their amorphous structure, variable opacity, and inconsistent visual signatures. By implementing a ResNet-50 backbone with Feature Pyramid Network, our model effectively captures these nonrigid entities across multiple scales and distances from rover cameras.
- **Planetary Science Impact:** Automated dust devil detection enhances our understanding of Mars' global dust budget and atmospheric dynamics. This technology not only improves scientific analysis efficiency but also establishes a foundation for potential onboard implementation in future missions, allowing real-time monitoring despite the computational constraints of spacecraft systems.
- **Beyond Manual Annotation:** While previous approaches relied heavily on human visual interpretation and limited orbital tracking, our method captures the full spectrum of dust devil activity, including phenomena that leave no visible surface marks, providing unprecedented insights into the Martian climate system.

Methods: Filtered Faster R-CNN Model Pipeline



Implementation Advantages [4]

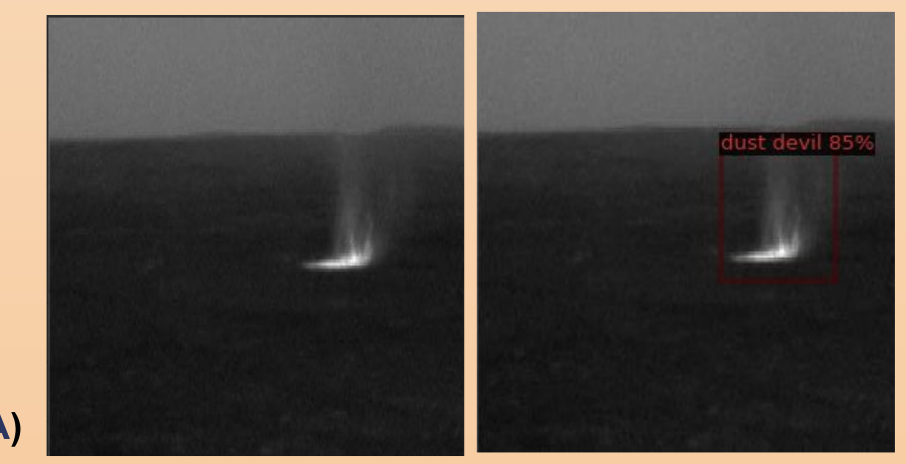
- **Boundary-Agnostic Detection:** The bounding box approach excels at identifying nonrigid, translucent phenomena like dust devils that lack the sharp edges required for accurate pixel-level segmentation.
- **Cross-Mission Applicability:** Model trained on diverse imagery from Spirit, Opportunity, and Perseverance rovers demonstrates robust performance across different instruments and mission phases.
- **Evaluation Framework:** Detection performance rigorously assessed using standard metrics including Average Precision across multiple IoU thresholds and specifically for small objects, crucial for distant dust devil detection.

Figure 2. Summary of the Fine-tuned Faster R-CNN model tailored for application with dust devils (adapted from standard Faster R-CNN model).

Preliminary Results

- **A: Spirit, Sol 532, NavCam**
  - Detection 1: dust devil, confidence=0.847, box=[197, 98, 290, 217]
- **B: Spirit, Sol 525, NavCam**
  - Detected 3 dust devils
  - Detection 1: dust devil, confidence=0.967, box=[315, 91, 344, 137]
  - Detection 2: dust devil, confidence=0.834, box=[208, 57, 229, 122]
  - Detection 3: dust devil, confidence=0.720, box=[335, 84, 344, 140]
- **C: Spirit, Sol 1120, NavCam**
  - Detected and tracked a dust devil with varying confidence frame-to-frame.

A)



B)

C)

Sample videos are available at: https://github.com/Kacy-SME/Martian-Dust-Devil-Detection/tree/main (QR code below).

Conclusion & Future Work

Developed a two-stage pipeline for efficient dust devil detection in Mars rover imagery: Our comprehensive approach combines preprocessing filters to remove unsuitable images followed by a Faster R-CNN with ResNet-50 backbone and Feature Pyramid Network, effectively detecting nonrigid, low-opacity dust devils that traditional methods frequently miss.

- **Demonstrated clear advantages over generic object detection models:** Our fine-tuned model significantly outperforms general-purpose architectures, highlighting the critical importance of domain-specific training for specialized atmospheric phenomena detection across multiple rover platforms and mission phases.
- **Established foundation for onboard implementation in future Mars missions:** This model could enable intelligent data prioritization, allowing rovers to retain high-resolution imagery of dust devil activity while applying aggressive compression to less scientifically valuable frames, optimizing limited bandwidth resources.

Future research opportunities: Integration of depth estimation techniques shows promise for extracting additional meteorological data including height, distance, and potentially wind speed measurements from detected dust devils. Further expansion of training datasets and temporal analysis of video sequences will enhance detection robustness and enable more comprehensive study of dust devil dynamics in the Martian atmosphere.

Code and Video

References

[1] Newman, C. E., S. R. Lewis, P. L. Read, and F. Forget, Modeling the Martian dust cycle, 1, Representations of dust transport processes, J. Geophys. Res., 107(E12), 5123, doi:10.1029/2002JE001910, 2002.
[2] Lorenz, R.D., Jackson, B.K. Dust Devil Populations and Statistics. Space Sci Rev 203, 277–297 (2016). https://doi.org/10.1007/s11214-016-0277-9
[3] Susan J. Conway, Valentin T. Bickel, Lori K. Fenton, Manish R. Patel, Helen C. Carson, Antoine Blouin, Justin Crevier, Evan Blanc, Bao Nhi Nguyen, James A. Holmes, Brian Jackson, Lonneke Roelofs, A global survey for dust devil vortices on mars using MRO context camera images enabled by neural networks, Planetary and Space Science, Volume 259, 2025
[4] Ren, S., He, K., Girshick, R., & Sun, J. (2015). Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks. *arXiv (Cornell University).* https://doi.org/10.48550/arxiv.1506.01497