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Development of 3D Neural Cellular Automata for Learning Spatio-Temporal Patterns

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Abstract

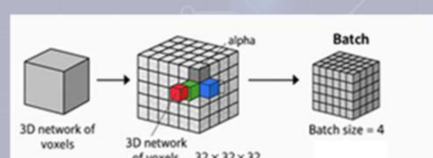
Neural Cellular Automata (NCA) provide a decentralized and parameter-efficient framework for learning spatial dynamics through local update rules. While prior research has primarily focused on two-dimensional representations, many computer vision and volumetric processing tasks require native three-dimensional modeling. In this work, we develop a fully 3D voxel-based Neural Cellular Automata architecture capable of learning geometric transformations in volumetric space. The model integrates a stabilized 3D Laplacian perception mechanism, bounded state updates, and noise-regularized optimization to ensure robust convergence. Experimental evaluation on a sphere-to-cube transformation task demonstrates stable learning behavior and accurate volumetric morphing. The proposed approach offers a lightweight alternative to full 3D convolutional networks for structured volumetric pattern generation and geometric modeling.

The purpose of the research

Three-dimensional data is fundamental in computer vision tasks such as medical imaging, volumetric reconstruction, and 3D geometric modeling. However, most Neural Cellular Automata (NCA) models have been limited to two-dimensional grids. The purpose of this research is to design and implement a fully three-dimensional Neural Cellular Automata (3D NCA) framework capable of learning volumetric geometric transformations using decentralized local update rules. The study investigates whether stable self-organizing behavior can emerge in 3D voxel grids under computational constraints.

Research method

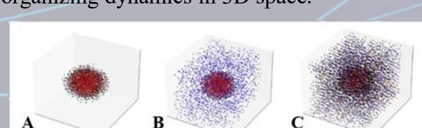
The model operates on a 32×32×32 voxel grid with four channels (RGBA), normalized to the range [0, 1]. Training is performed using mini-batches (Batch Size = 4) for improved stability. Voxel states are updated through a learned local rule based on a 3D Laplacian kernel followed by Tanh activation, with updates limited to 10% of the computed change to ensure stability. The network is trained using MSE loss with Gaussian noise injection ($\sigma = 0.01$) for robustness. Optimization is performed using Nadam with a learning rate of 5×10^{-4} and exponential decay over 2000 iterations.



Schematic representation of the 3D voxel network used in the proposed NCA model

Practical or simulation results

The primary experiment evaluates the model's ability to transform a spherical volumetric structure into a cubic target configuration. The model gradually learns geometric reshaping through repeated application of local rules. The training process exhibits bounded oscillations while maintaining overall stability. Complex shapes such as torus and heart forms were tested; however, due to computational constraints, stable convergence was consistently observed only in the sphere-to-cube task. The results demonstrate successful volumetric morphing, stable convergence behavior, robust performance under noise perturbations, emergent self-organizing dynamics in 3D space.



Process of Sphere-to-Cube Volume Transformation. A) Stage from 50, B) Stage from 250, C) Stage from 500

conclusion

In this study, we developed a fully three-dimensional Neural Cellular Automata framework for learning volumetric geometric transformations through decentralized local update rules. The proposed 3D voxel-based model demonstrates that stable and structured global behavior can emerge from simple differentiable local interactions. Experimental results on the sphere-to-cube transformation task confirm that the model achieves robust convergence while maintaining computational efficiency under limited hardware resources. Compared to conventional 3D convolutional architectures, the proposed approach provides a parameter-efficient and interpretable alternative for volumetric pattern generation. These findings support the feasibility of extending Neural Cellular Automata to practical 3D computer vision and volumetric modeling applications.

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