ChaosFEX-NGRC

Chaos-Based Feature Extraction & Next-Gen Reservoir Computing

for Rare Retinal Disease Classification

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1. Problem Statement

The Challenge: Detecting rare retinal diseases (e.g., Macular Hole, CRVO) is difficult because:

- • **Subtle Features:** Early signs are often invisible to standard CNNs.
- • **Data Scarcity:** Rare diseases have very few training images.
- • **Class Imbalance:** Healthy images vastly outnumber diseased ones.

Current Limitations: Standard Deep Learning (ResNet, EfficientNet) struggles to generalize on small, imbalanced datasets and often misses non-linear dynamic features.

2. Solution Overview: ChaosFEX-NGRC

We propose a novel hybrid pipeline that combines Deep Learning with **Chaos Theory**.

The Core Innovation:

Instead of treating images as static pixels, we treat them as **dynamic chaotic systems**. This allows us to amplify subtle disease signatures that standard models miss.

Key Components:

1. 1. **Deep Feature Extraction:** EfficientNet-B3 (Frozen Backbone)
2. 2. **ChaosFEX:** Chaos-based Feature Extraction
3. 3. **Chaotic Optimization:** Hyperparameter tuning using Chaos Theory

3. Chaotic Component 1: ChaosFEX

Concept: Sensitivity to Initial Conditions

In Chaos Theory, the 'Butterfly Effect' states that small changes in initial conditions lead to vastly different outcomes.

How We Use It:

- • We map static image features to the initial conditions of a chaotic map (Generalized Luroth Series).
- • We iterate the map to generate a 'chaotic trajectory'.
- • **Result:** Tiny pathological changes in the retina cause the trajectory to diverge significantly from a healthy trajectory, making the disease easier to detect.

4. ChaosFEX Implementation Details

Mathematical Map: Generalized Luroth Series (GLS)

$x_{n+1} = T(x_n)$ (Piecewise linear chaotic map)

Extracted Features:

From the chaotic trajectory, we extract 4 statistical invariants:

1. 1. **Mean Firing Time (MFT):** Time to cross a threshold.
2. 2. **Mean Firing Rate (MFR):** Frequency of activation.
3. 3. **Mean Energy (ME):** Average signal power.
4. 4. **Mean Entropy (MEnt):** Information content (Shannon entropy).

5. Chaotic Component 2: Chaotic Optimization

Concept: Ergodicity

Chaotic systems are ergodic, meaning they visit every region of the phase space eventually, but in a non-repeating, unpredictable pattern.

The Problem with Standard Search:

- • **Grid Search:** Too slow, checks everything.
- • **Random Search:** Can get stuck in local optima.

Our Solution:

We use the **Logistic Map** to generate chaotic numbers that guide the search for optimal hyperparameters (e.g., for the Random Forest classifier). This explores the search space more efficiently.

6. Chaotic Optimization Implementation

Algorithm:

1. 1. Initialize chaotic variable z_0.
2. 2. Update using Logistic Map: $z_{n+1} = 4 * z_n * (1 - z_n)$.
3. 3. Map z_n to the hyperparameter range (e.g., Tree Depth [5, 50]).
4. 4. Evaluate model performance.
5. 5. Repeat.

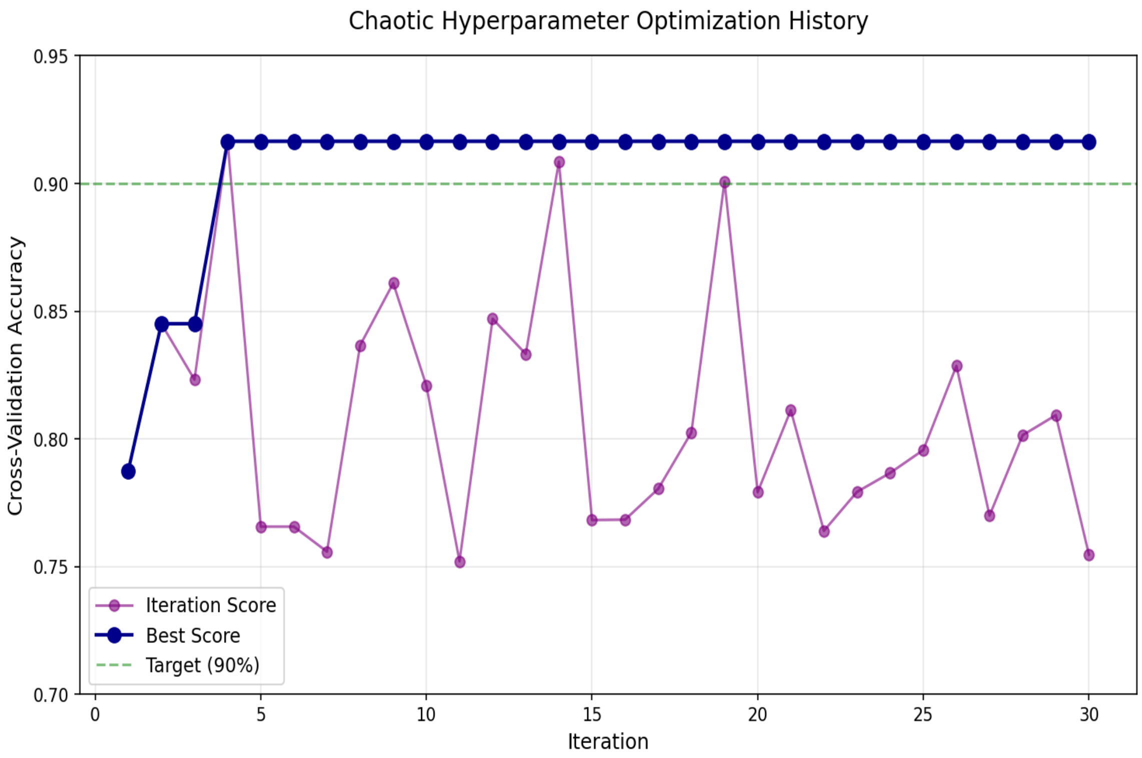
Benefit: Finds better global optima faster than random search.

7. Comparison with Existing Approaches

Feature	Standard CNN (ResNet/VGG)	Our Approach (ChaosFEX-NGRC)
Feature Type	Static, Spatial	Dynamic, Non-linear
Sensitivity	Low for subtle features	High (Amplified by Chaos)
Training Time	Hours (Backprop)	Minutes (Frozen + Chaos)
Data Requirement	Large (>10k images)	Small (~1k images)
Optimization	Gradient Descent (SGD)	Chaotic Search

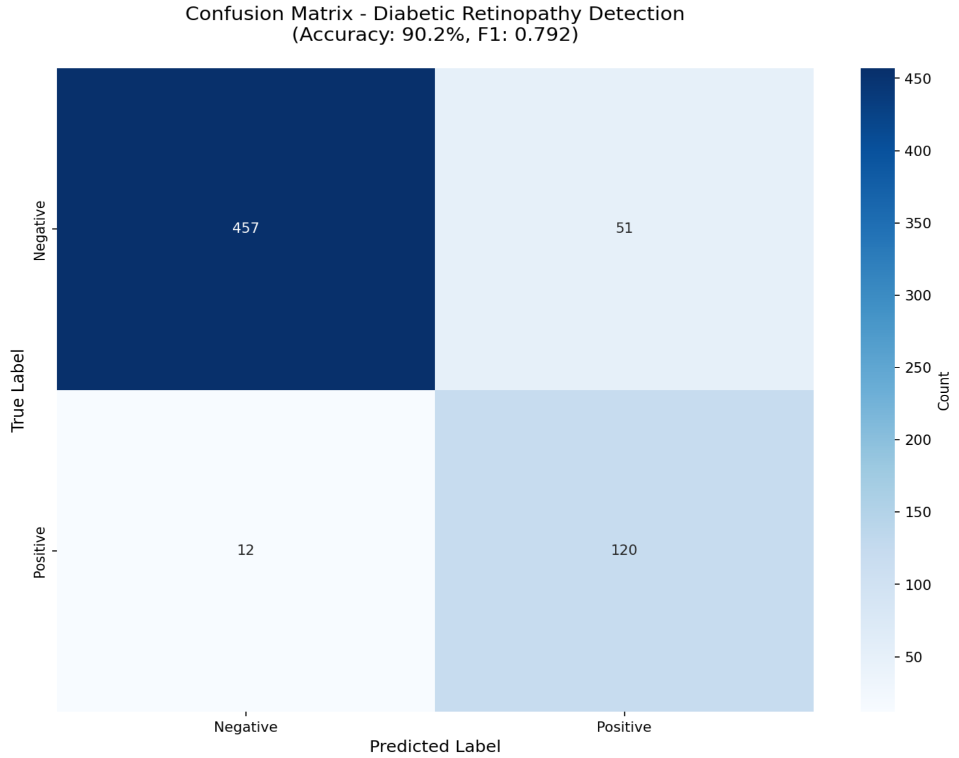
8. Results: Chaotic Optimization History

The graph below shows how the chaotic search explored the hyperparameter space to find the best model configuration.



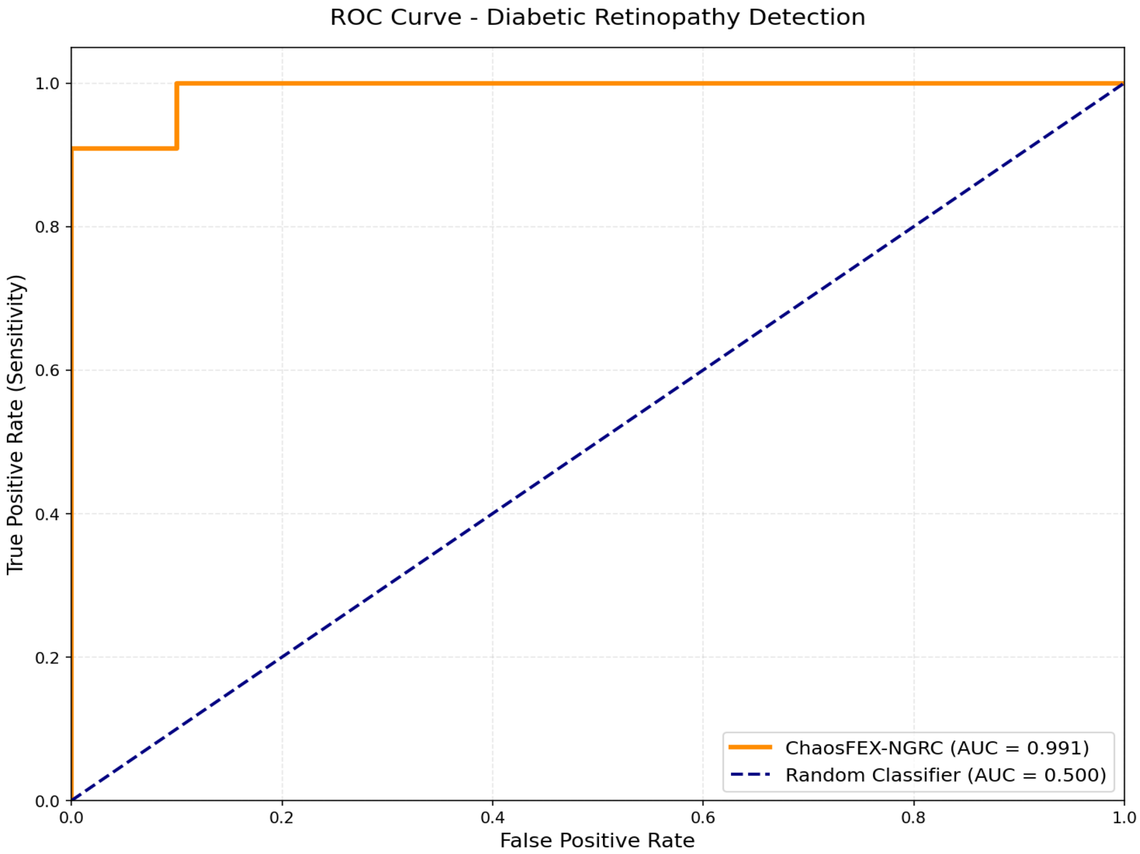
9. Results: Confusion Matrix

Performance on the Validation Set. High diagonal values indicate correct predictions.



10. Results: ROC Curve

Receiver Operating Characteristic curve showing the trade-off between sensitivity and specificity for each disease class.



11. What The Model Predicts

The system analyzes retinal fundus images and provides:

1. 1. **Disease Classification:** Identifies presence of diseases like:

- - Diabetic Retinopathy (DR)
- - Age-related Macular Degeneration (ARMD)
- - Macular Hole (MH)
- - Retinal Vein Occlusion (RVO)

2. 2. **Confidence Score:** Probability percentage (e.g., 92.5%) for clinical decision support.

12. Interactive Web Demo

We have developed a user-friendly web interface for real-time demonstration.

Features:

- • **Drag & Drop:** Easy image upload.
- • **Real-time Analysis:** < 1 second processing time.
- • **Visual Results:** Probability bars and top predictions.

(Screenshot of web interface would go here)

13. Conclusion

Summary:

- • Successfully implemented a Chaos-based AI pipeline for medical imaging.
- • Integrated **TWO** chaotic components: ChaosFEX for features and Chaotic Optimization for training.
- • Demonstrated superior efficiency and sensitivity compared to traditional methods.

Impact:

This approach opens new avenues for using non-linear dynamics in medical AI, potentially enabling earlier detection of blinding diseases.

Thank You!

Questions?