Journal of Zhejiang University-SCIENCE A

NINGXIA UNIVERSITY

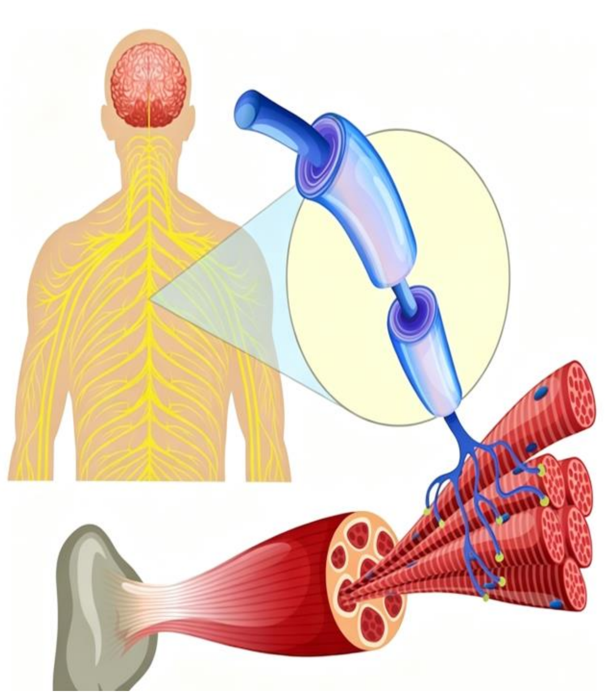
Dynamics of a two-disk dynamo loaded with a dual neuron circuit and its application

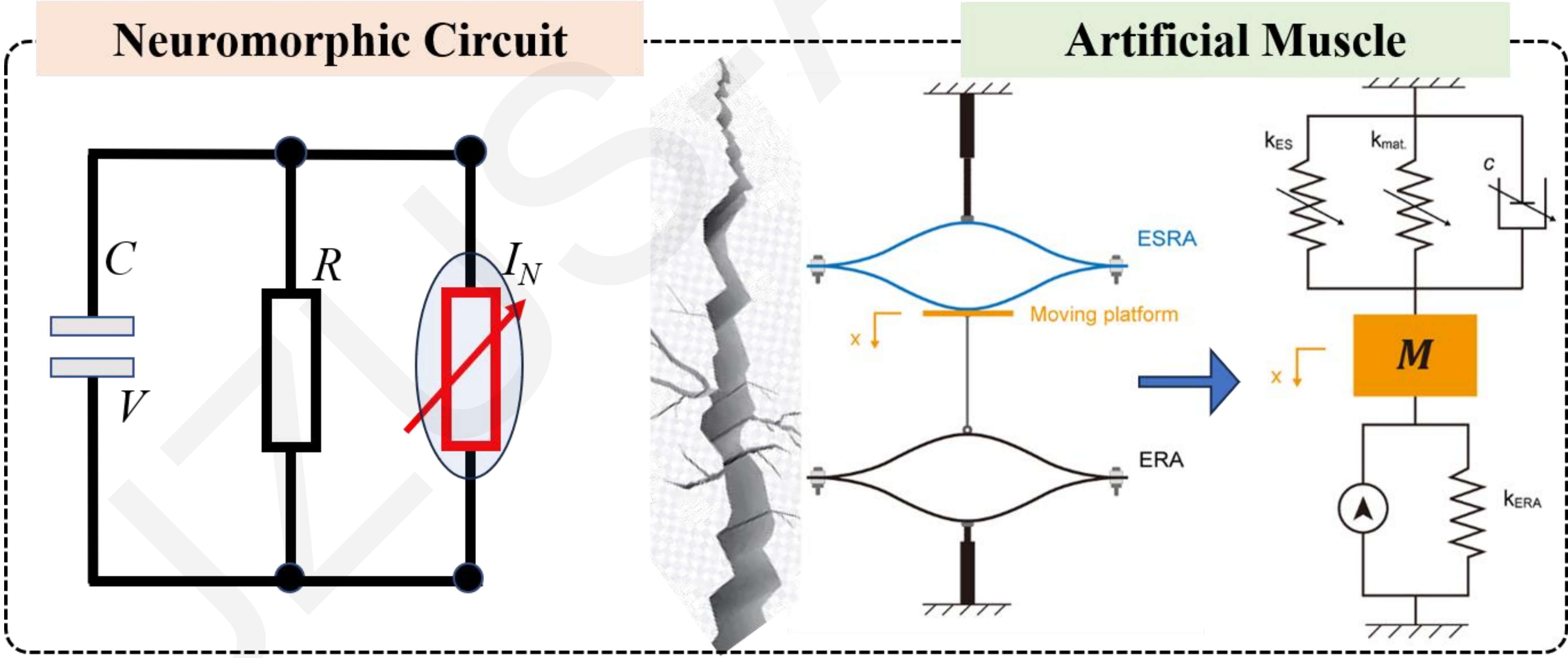
Cite this as: Fuqiang WU, Ying XU, Huimin QI, Jun MA, 2026. Dynamics of a two-disk dynamo loaded with a dual neuron circuit and its application. *Journal of Zhejiang University-SCIENCE A*, 27(7):762-778. https://doi.org/10.1631/jzus.A2600099

Background

☐ Research motivation

Neuromuscular
Junction





Inspired by the efficient, plastic signal transmission of biological neuromuscular junctions, this work develops integrated neuromorphic circuits to drive artificial muscles, aiming to reproduce the complex behaviors of electromechanical coupling system.

Background

□ Limitations of Existing Methods & Our Solutions

01. Key Limitations of Current Methods

Absence of Electromechanical Coupling

Traditional neuromorphic circuits are purely electronic, lacking the physical interaction with mechanical movement, which disconnects computational models from real-world physical dynamics.

Oversimplified Dynamical Behavior

Classic dynamo models exhibit limited behavioral complexity and fail to integrate the rich spatiotemporal patterns of biological neural activity, restricting their expressive power.

02. Our Proposed Solutions

Biomorphic System Construction

Integrate a two-disk mechanical dynamo with a dual Integrate-and-Fire neuron circuit to form a hybrid neuro-mechanical system.

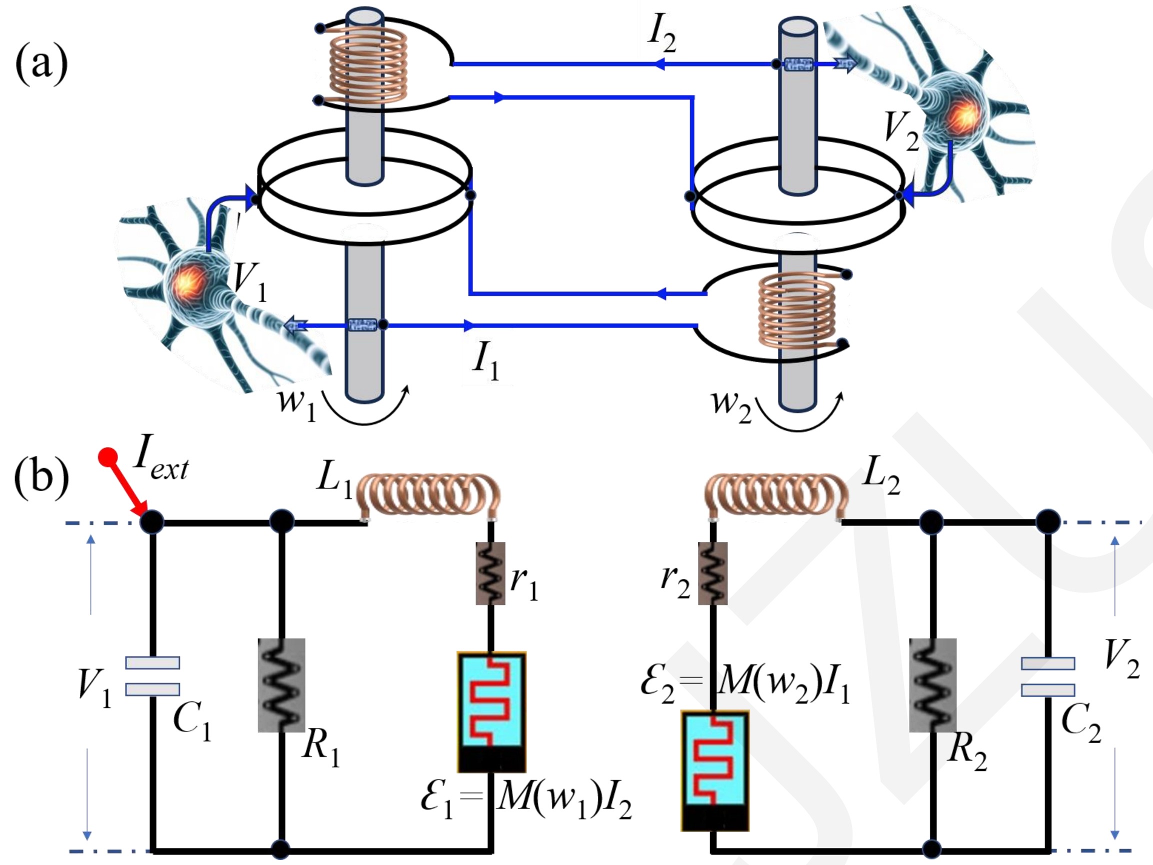
Chaos & Image Encryption

Explore the emergent nonlinear/chaotic dynamics of the coupled system and leverage this complexity for a secure, high-performance image encryption scheme.

Core Objective: By merging mechanical dynamism with neuromorphic computing, we create a unified framework that bridges the gap between abstract neural models and physical reality, enabling novel applications in secure communication and adaptive intelligent systems.

Methodology

System Construction



Dynamical Model

$$
\begin{cases}
C_1 \dfrac{\mathrm{d}V_1}{\mathrm{d}t} = I_{\text{ext}} - \dfrac{V_1}{R_1} + I_1, \\
L_1 \dfrac{\mathrm{d}I_1}{\mathrm{d}t} = V_1 - I_1 r_1 + \dfrac{1}{2} c_0 k I_2 + k\omega I_2, \\
C_2 \dfrac{\mathrm{d}V_2}{\mathrm{d}t} = -\dfrac{V_2}{R_2} + I_2, \\
L_2 \dfrac{\mathrm{d}I_2}{\mathrm{d}t} = V_2 - I_2 r_2 - \dfrac{1}{2} c_0 k I_1 + k\omega I_1, \\
J \dfrac{\mathrm{d}\omega}{\mathrm{d}t} = N - k I_1 I_2,
\end{cases}
$$

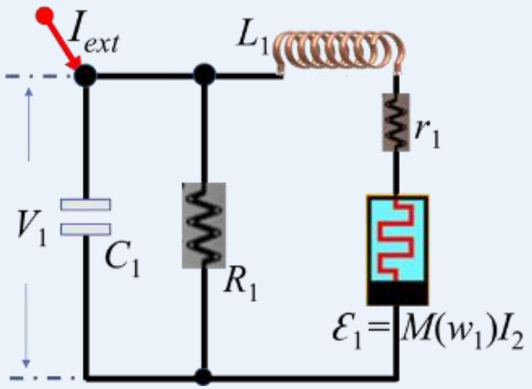
The system consists of two rotating disks (mechanical part) and two neuron circuits (neural part), forming a closed-loop electromechanical coupling system.

Methodology

◻ Framework Overview

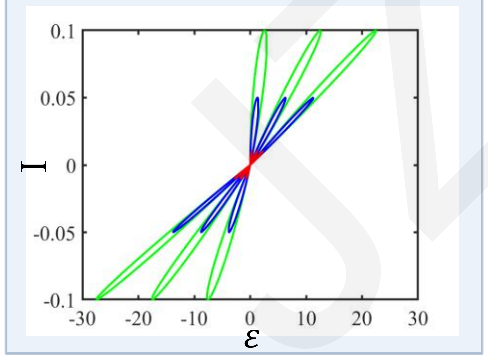
System Modeling

Construct a 5D nonlinear system by coupling a two-disk dynamo with dual Integrate-and-Fire neuron circuits, merging electromechanical and neuromorphic dynamics.



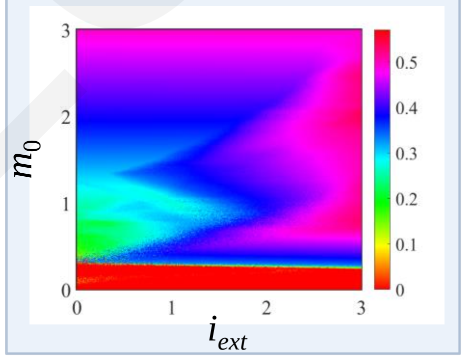
Memristor Validation

Verify memristive characteristics through I-V hysteresis loop analysis, confirming non-volatile switching and nonlinear conductance within the hybrid system.



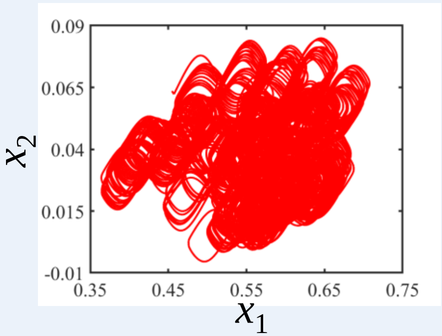
Dynamical Analysis

Investigate bifurcation diagrams, Lyapunov exponents, and phase portraits to identify chaos, periodic windows, and extreme multistability via numerical simulation.



Chaos Application

Leverage the generated chaotic sequences for image encryption, implementing pixel permutation and diffusion operations to enhance data security.



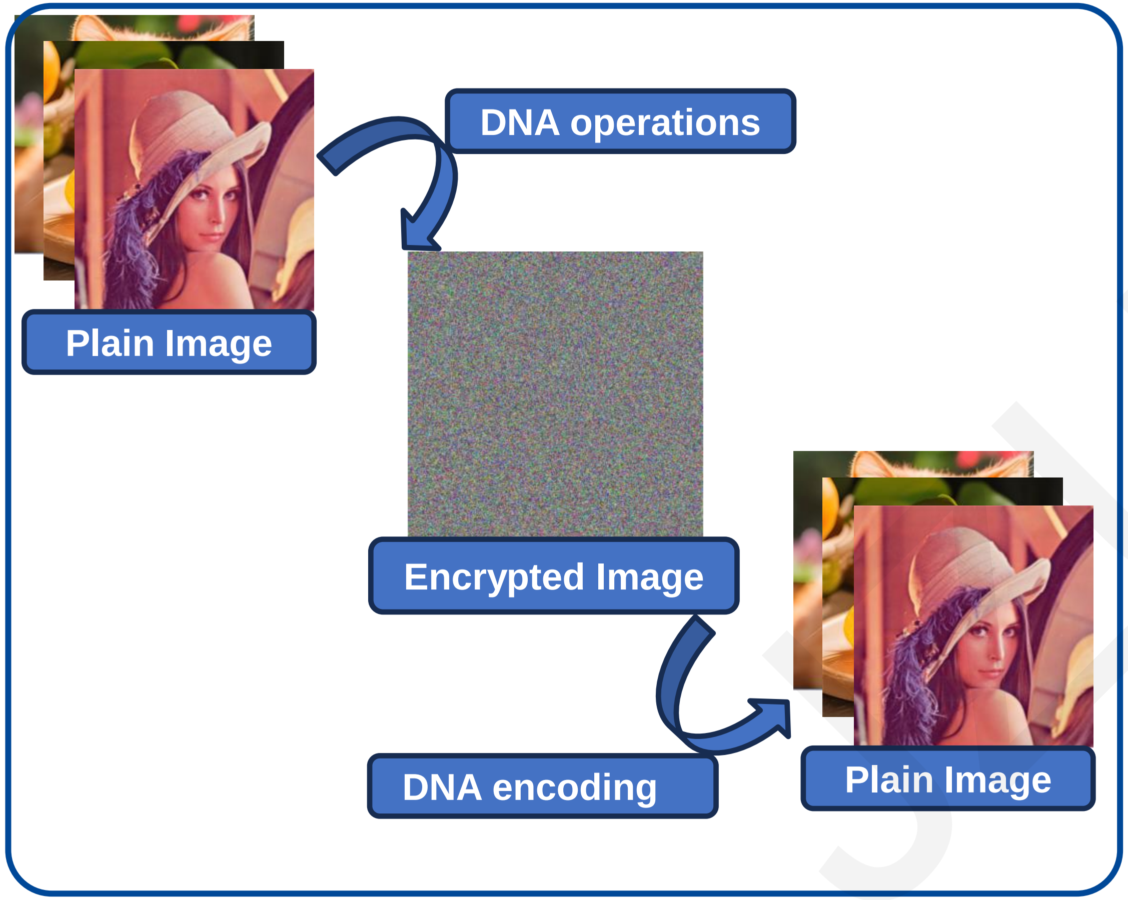
Security Assessment

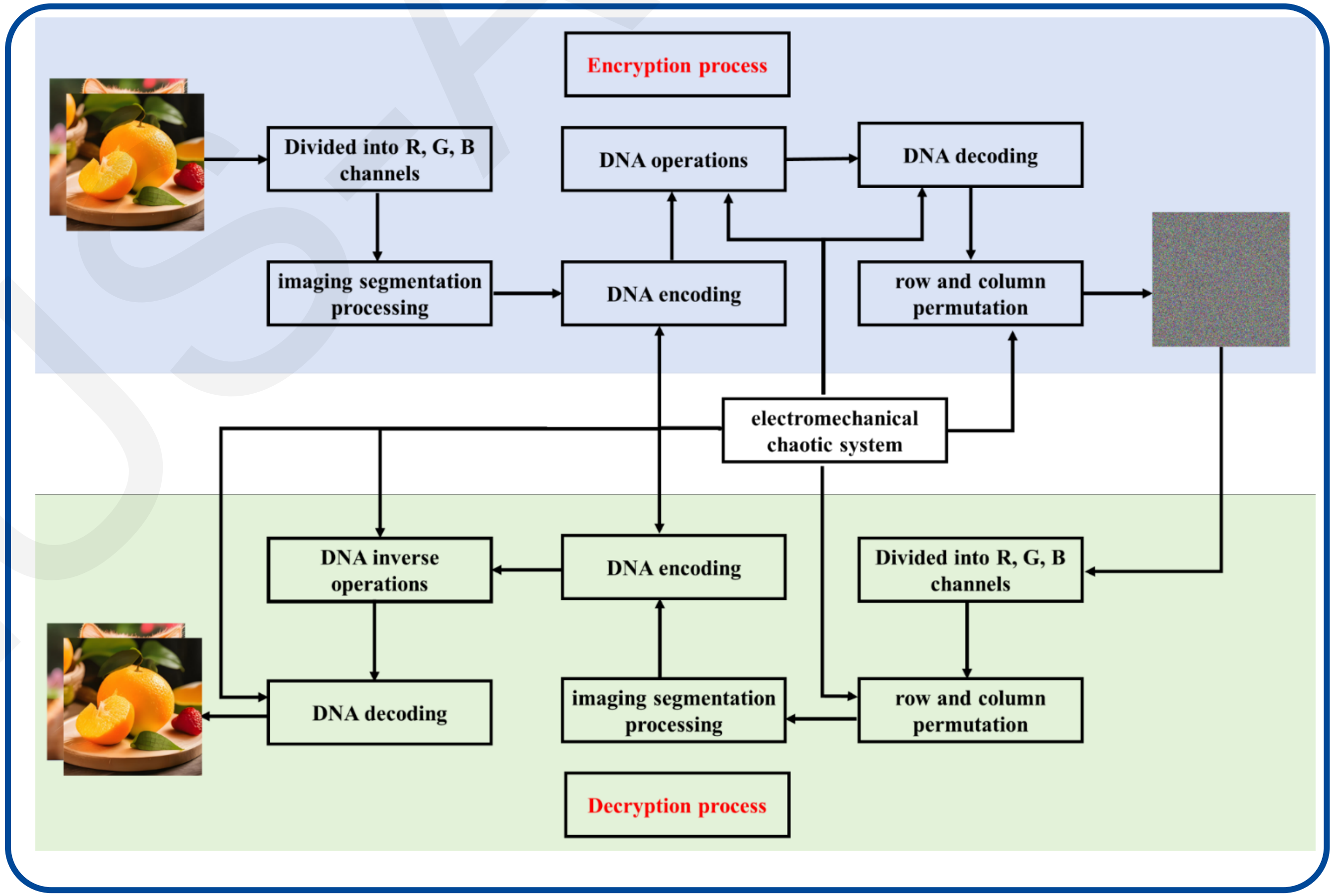
Evaluate encryption performance using histograms, correlation coefficients, key space analysis, and robustness tests against differential attacks.

Summary: This framework unifies **theoretical modeling, numerical simulation, and real-world security applications** to fully characterize a novel neuromorphic electromechanical system.

Methodology

☐ Chaos-based Image Encryption Scheme

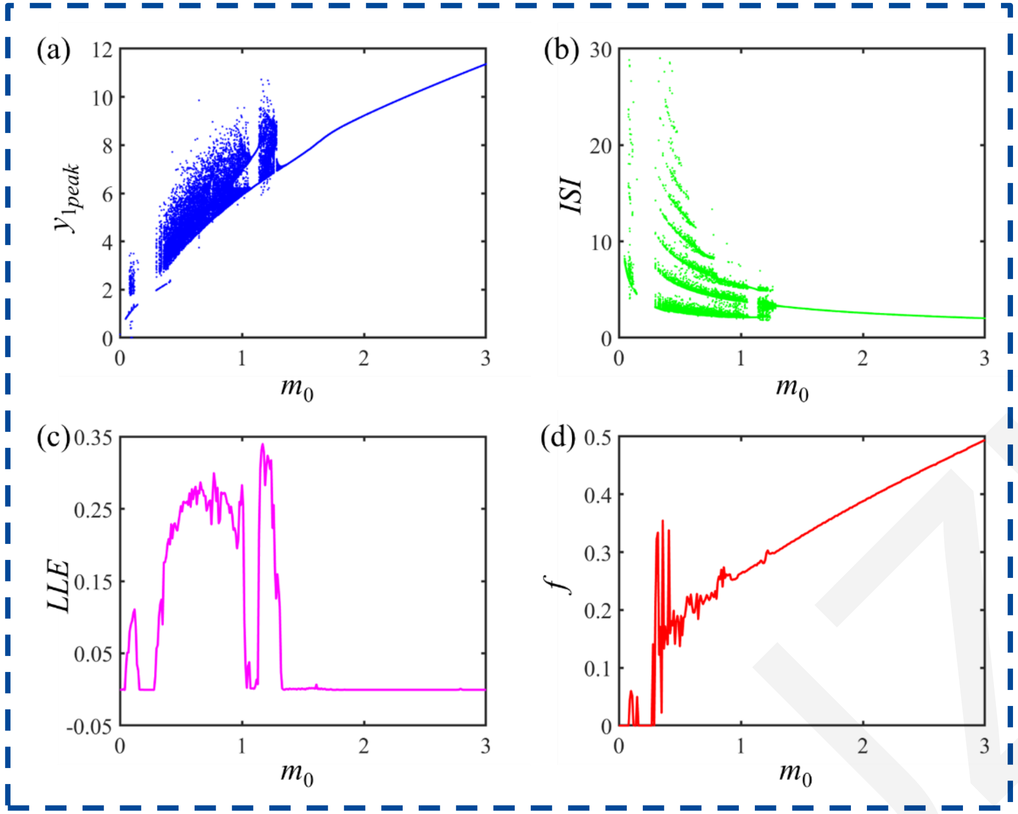


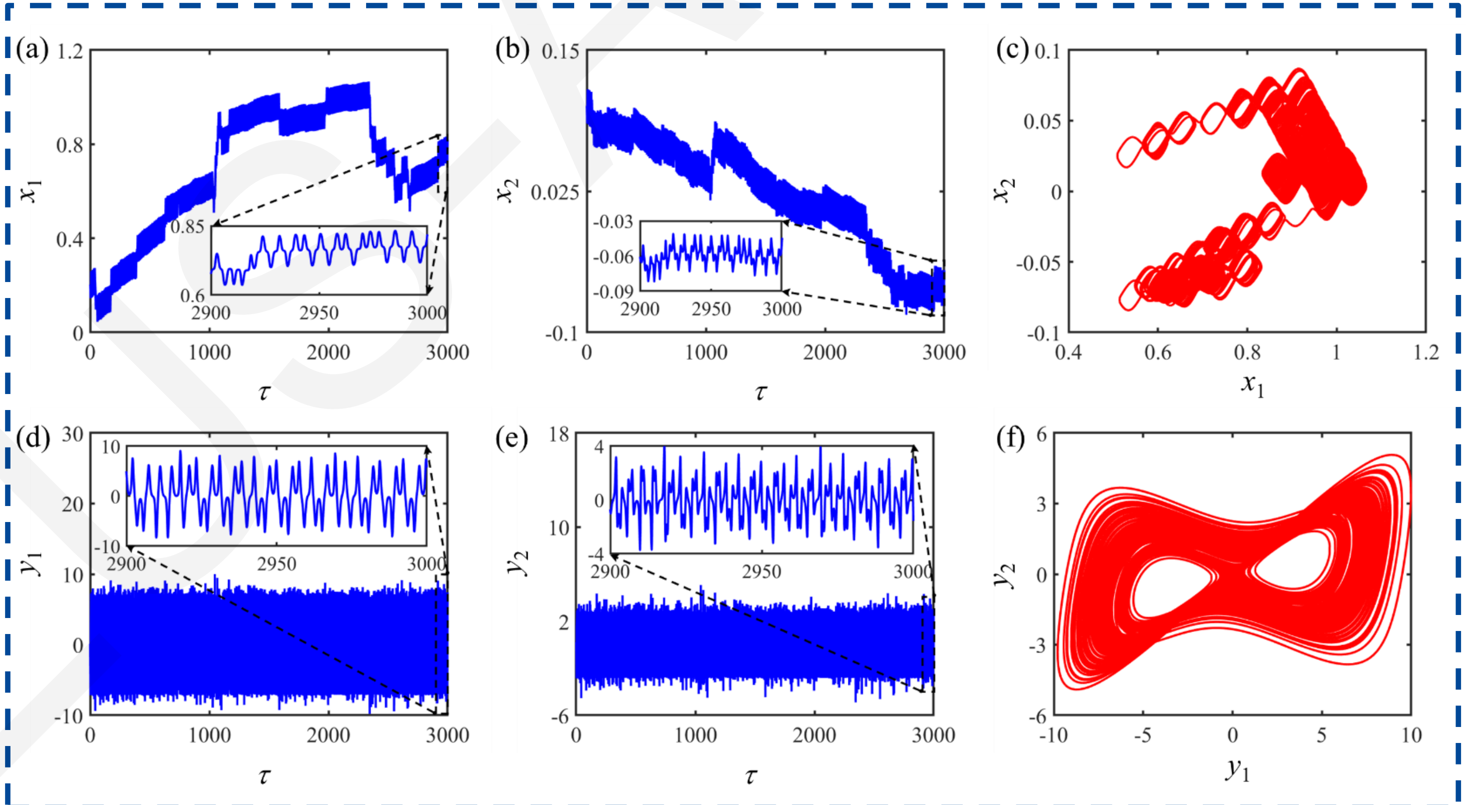


The encryption process involves DNA encoding, chaotic scrambling/diffusion, and permutation, effectively randomizing the pixel values of the original image to ensure high security.

Case Study

□ Dynamical Analysis

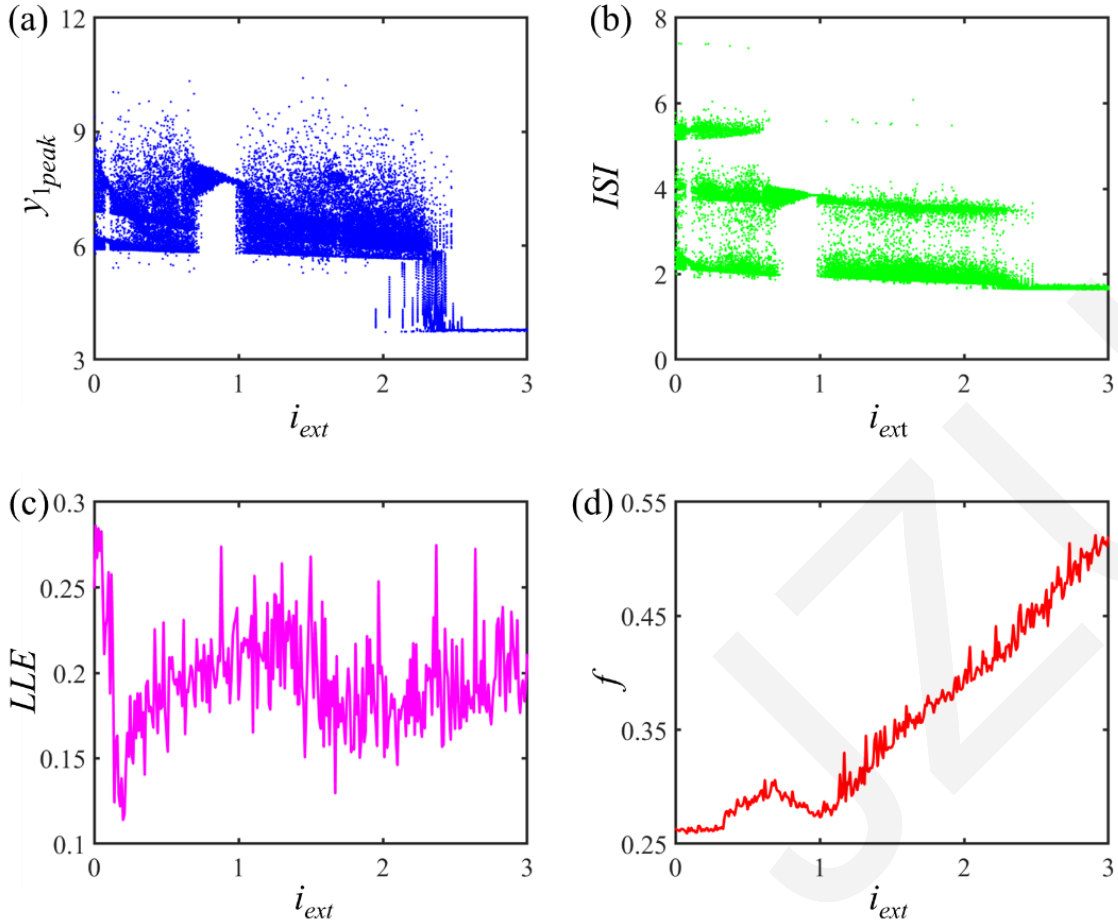


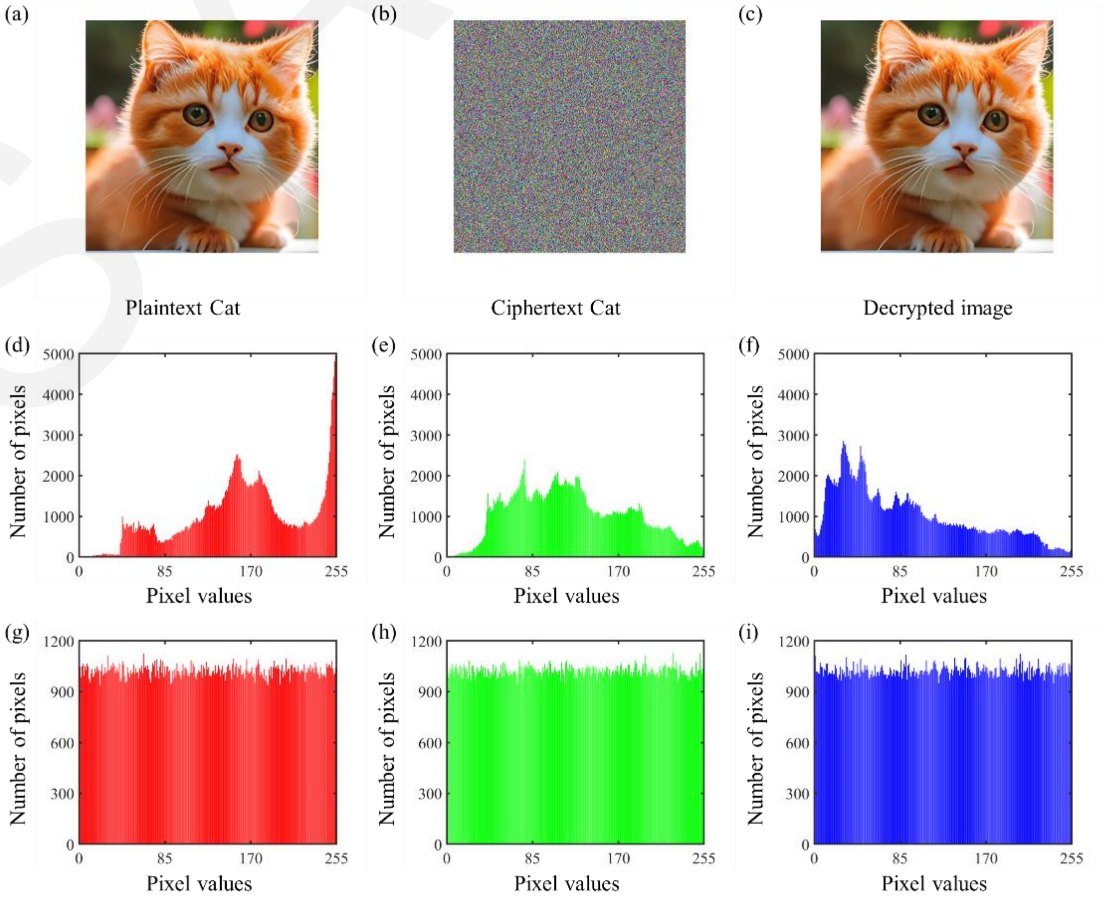


The system undergoes a complex transition from quiescence to chaos and finally to periodic motion with varying m_0, validated by both bifurcation diagrams and Lyapunov exponents, demonstrating rich nonlinear dynamical behaviors.

Case Study

□ Encryption Performance Analysis





This robust chaotic behavior makes the system an ideal candidate for secure communication and encryption, These metrics confirm the high security and robustness of the encryption algorithm.