# Novelty Assessment Report

**Paper**: Feedback-driven recurrent quantum neural network universality

**PDF URL**: https://openreview.net/pdf?id=248ysaRatx

**Venue**: ICLR 2026 Conference Submission

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## Abstract

Quantum reservoir computing uses the dynamics of quantum systems to process temporal data, making it particularly well-suited for machine learning with noisy intermediate-scale quantum devices. Recent developments have introduced feedback-based quantum reservoir systems, which process temporal information with comparatively fewer components and enable real-time computation while preserving the input history. Motivated by their promising empirical performance, in this work, we study the approximation capabilities of feedback-based quantum reservoir computing. More specifically, we are concerned with recurrent quantum neural networks, which are quantum analogues of classical recurrent neural networks. Our results show that regular state-space systems can be approximated using quantum recurrent neural networks without the curse of dimensionality and with the number of qubits only growing logarithmically in the reciprocal of the prescribed approximation accuracy. Notably, our analysis demonstrates that quantum recurrent neural networks are universal with linear readouts, making them both powerful and experimentally accessible. These results pave the way for practical and theoretically grounded quantum reservoir computing with real-time processing capabilities.



## Core Task Landscape

This paper addresses: **Approximation Capabilities of Feedback-Based Quantum Reservoir Computing**

A total of **27 papers** were analyzed and organized into a taxonomy with **18 categories**.

### Taxonomy Overview

The research landscape has been organized into the following main categories:

- **Theoretical Foundations and Approximation Guarantees**
- **Feedback Mechanisms and Measurement Protocols**
- **Performance Analysis and Task-Specific Applications**
- **Experimental Implementations and Hardware Platforms**
- **Alternative Quantum Reservoir Architectures**
- **Recurrent Quantum Neural Network Frameworks**

### Complete Taxonomy Tree

- Approximation Capabilities of Feedback-Based Quantum Reservoir Computing Survey Taxonomy
- Theoretical Foundations and Approximation Guarantees
  - Universal Approximation and Complexity Analysis ★ (2 papers)
  - [0] Feedback-driven recurrent quantum neural network universality (Anon et al., 2026) View paper
  - [23] Temporal Information Processing on Noisy Quantum Computers (Chen Jiayin, 2022) View paper
  - Nonlinear Dynamics and Convergent Systems (2 papers)
  - [24] Nonlinear Convergent Dynamics for Temporal Information Processing on Novel Quantum and Classical Devices (Jiayin, 2022) View paper
  - [27] Nonlinear Autoregression With Convergent Dynamics on Novel Computational Platforms (Chen, 2021) View paper
- Feedback Mechanisms and Measurement Protocols
  - Weak Measurement and Continuous Monitoring (3 papers)
  - [2] Feedback-enhanced quantum reservoir computing with weak measurements (Setoyama, 2025) View paper
  - [6] Reservoir computing using measurement-controlled quantum dynamics (A. H. Abbas, 2024) View paper
  - [7] Harnessing quantum back-action for time-series processing (Giacomo Franceschetto, 2024) View paper
  - Mid-Circuit Measurement Protocols (1 papers)
  - [5] Feedback connections in quantum reservoir computing with mid-circuit measurements (Krishnakumar, 2025) View paper
  - Feedback-Enhanced Temporal Processing (2 papers)
  - [1] Feedback-driven quantum reservoir computing for time-series analysis (Kaito Kobayashi, 2024) View paper
  - [15] Minimalistic and Scalable Quantum Reservoir Computing Enhanced with Feedback (Zhu, 2024) View paper
- Performance Analysis and Task-Specific Applications
  - Chaotic Systems and Time-Series Forecasting (3 papers)
  - [3] Optimal training of finitely sampled quantum reservoir computers for forecasting of chaotic dynamics (Osama Ahmed, 2025) View paper
  - [9] Hybrid quantum-classical reservoir computing for simulating chaotic systems (Wudarski, 2023) View paper
  - [13] Time-series forecasting with multiphoton quantum states and integrated photonics (Rosario Di Bartolo, 2025) View paper
  - Memory Capacity Characterization (1 papers)
  - [10] Characterizing the memory capacity of transmon qubit reservoirs (Samudra Dasgupta, 2022) View paper
  - Classification Tasks (1 papers)

    - [25] Iris Flower Recognition Using Four-Channels Ring Photonic Reservoir Computing Based on Unidirectional Coupled VCSELs (Qian Yu, 2023) View paper
    - Reduced-Order Modeling (1 papers)
    - [16] Higher order quantum reservoir computing for non-intrusive reduced-order models (Maulik, 2024) View paper
- Experimental Implementations and Hardware Platforms
    - Continuous-Variable Photonic Platforms (3 papers)
    - [4] Experimental memory control in continuous variable optical quantum reservoir computing (Paparelle, 2025) View paper
    - [14] Measurement-based continuous-variable quantum reservoir computing (Iris Paparelle, 2025) View paper
    - [22] Influence of Measurements on Continuous Variable Quantum Reservoir Computing (GarcÃa-Beni, 2021) View paper
    - Discrete Photonic Systems (1 papers)
    - [12] Experimental photonic quantum memristor (Michele Spagnolo, 2022) View paper
    - Alternative Physical Platforms (2 papers)
    - [8] Timeâ□□Multiplexed Reservoir Computing with Quantumâ□□Dot Lasers: Impact of Chargeâ□□Carrier Scattering Timescale (Huifang Dong, 2025) View paper
    - [20] Time-multiplexed Reservoir Computing with Quantum-Dot Lasers: Does more complexity lead to better performance? (Dong Hui-fang, 2024) View paper
- Alternative Quantum Reservoir Architectures
    - Higher-Order and Hybrid Architectures (1 papers)
    - [19] Higher-order quantum reservoir computing (Tran Quoc Hoan, 2020) View paper
    - Non-Markovian and Memory-Enhanced Dynamics (1 papers)
    - [18] Hamiltonian-Driven Architectures for Non-Markovian Quantum Reservoir Computing (Sasaki Daiki, 2025) View paper
    - Dissipation as Computational Resource (1 papers)
    - [17] Dissipation as a resource for Quantum Reservoir Computing (Antonio Sannia, 2024) View paper
    - Squeezing and Quantum Resource Utilization (1 papers)
    - [21] Squeezing as a resource for time series processing in quantum reservoir computing (Jorge GarcÃa-Beni, 2023) View paper
    - Quantum Walk-Based Approaches (1 papers)
    - [26] Feedback-assisted quantum search by continuous-time quantum walks (Candeloro, 2022) View paper
- Recurrent Quantum Neural Network Frameworks (1 papers)
    - [11] Reservoir computing via quantum recurrent neural networks (Chen, 2022) View paper

### Narrative

Core task: approximation capabilities of feedback-based quantum reservoir computing. The field explores how quantum systems with measurement-driven feedback can serve as computational reservoirs for temporal processing tasks. The taxonomy reveals several complementary perspectives: Theoretical Foundations examine universal approximation properties and complexity bounds that establish what these systems can represent in principle; Feedback Mechanisms investigate how measurement protocols and control loops shape reservoir dynamics; Performance Analysis evaluates task-specific benchmarks ranging from time-series forecasting to nonlinear system emulation; Experimental Implementations address hardware constraints across photonic, superconducting, and quantum-dot platforms; Alternative Architectures explore designs without explicit feedback or with novel coupling schemes; and Recurrent Quantum Neural Network Frameworks situate reservoir computing within broader quantum machine learning paradigms. Representative works such as Feedback Quantum Reservoir[1] and Weak Measurement Reservoir[2] illustrate how measurement strength and feedback timing critically influence memory and nonlinearity, while experimental studies like Time-Multiplexed Quantum-Dot[8] and Transmon Memory Capacity[10] demonstrate practical trade-offs between coherence, readout fidelity, and computational capacity.

A central tension emerges between theoretical guarantees and experimental feasibility: many studies pursue optimal forecasting strategies (Optimal Quantum Forecasting[3]) or leverage dissipation as a computational resource (Dissipation as Resource[17]), yet hardware noise and limited coherence times constrain real-world performance (Noisy Temporal Processing[23]). Feedback Recurrent Quantum[0] contributes to the theoretical foundations by rigorously analyzing universal approximation and complexity within this feedback-driven paradigm, closely aligning with formal studies of recurrent quantum architectures (Quantum Recurrent Networks[11]) and convergent dynamics (Nonlinear Convergent Dynamics[24]). Compared to neighboring work on noisy environments (Noisy Temporal Processing[23]), Feedback Recurrent Quantum[0] emphasizes provable approximation capabilities rather than empirical robustness, offering complementary insights into what feedback-based reservoirs can achieve under idealized conditions and how complexity scales with system size and feedback depth.

## Related Works in Same Category

The following **1 sibling papers** share the same taxonomy leaf node with the original paper:

### 1. Temporal Information Processing on Noisy Quantum Computers

**Authors**: Chen Jiayin, Nurdin, Hendra I., Yamamoto Naoki | **Year/Venue**: 2022 • arXiv (Cornell University) | **URL**: View paper

#### Abstract

The combination of machine learning and quantum computing has emerged as a promising approach for addressing previously untenable problems. Reservoir computing is an efficient learning paradigm that utilizes nonlinear dynamical systems for temporal information processing, i.e., processing of input sequences to produce output sequences. Here we propose quantum reservoir computing that harnesses complex dissipative quantum dynamics. Our class of quantum reservoirs is universal, in that any nonline...

#### Relationship Analysis

Both papers belong to the Universal Approximation and Complexity Analysis category, focusing on proving universality of quantum reservoir computing systems with theoretical guarantees. They overlap in establishing that quantum reservoir systems can approximate fading memory maps and analyzing approximation capabilities for temporal information processing. The original paper specifically analyzes feedback-driven recurrent quantum neural networks with detailed complexity bounds showing logarithmic qubit scaling and derivative approximation guarantees, while the candidate paper proposes a broader class of dissipative quantum reservoir computing systems with experimental validation on cloud-based quantum computers but less detailed complexity analysis.

## Contributions Analysis

**Overall novelty summary.** The paper establishes approximation bounds for recurrent quantum neural networks (RQNNs) with feedback, demonstrating logarithmic qubit scaling in approximation accuracy without curse of dimensionality. It resides in the 'Universal Approximation and Complexity Analysis' leaf under 'Theoretical Foundations and Approximation Guarantees', which contains only two papers total. This sparse population suggests the work addresses a relatively underexplored theoretical niche within quantum reservoir computing, focusing on rigorous complexity guarantees rather than empirical performance or hardware constraints that dominate other branches of the taxonomy.

The taxonomy reveals neighboring theoretical work in 'Nonlinear Dynamics and Convergent Systems' examining autoregressive models and convergent substrates, while 'Feedback Mechanisms and Measurement Protocols' explores measurement-driven control strategies that enable the feedback architectures analyzed here. The paper bridges these areas by providing formal approximation guarantees for feedback-based systems, complementing empirical studies in 'Performance Analysis' that evaluate forecasting and memory capacity without theoretical bounds. Its focus on linear readouts distinguishes it from alternative architectures leveraging dissipation, non-Markovian dynamics, or higher-order structures, which pursue computational advantages through different physical mechanisms rather than approximation-theoretic foundations.

Among seventeen candidates examined across three contributions, none were identified as clearly refuting the claimed results. The first contribution (approximation bounds without curse of dimensionality) examined two candidates with no refutations; the second (universality with linear readouts) examined five candidates with no refutations; the third (feedforward QNN approximation results) examined ten candidates with no refutations. This limited search scope—covering top-K semantic matches and citation expansion rather than exhaustive field coverage—suggests the specific combination of feedback-based RQNNs, logarithmic qubit scaling, and linear readout universality has not been extensively addressed in prior accessible literature, though the analysis cannot rule out relevant work outside the examined candidate set.

Based on the seventeen candidates examined, the work appears to occupy a distinct theoretical position within quantum reservoir computing, addressing approximation complexity for feedback-driven recurrent architectures with formal guarantees. The sparse population of its taxonomy leaf and absence of refuting candidates among examined papers suggest novelty in this specific formulation, though the limited search scope means potentially relevant theoretical work in quantum complexity theory or classical recurrent network approximation may exist beyond the candidate pool. The analysis covers semantic proximity and citation links but does not exhaustively survey adjacent mathematical frameworks.

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This paper presents **3 main contributions**, each analyzed against relevant prior work:

## Contribution 1: Approximation bounds for recurrent quantum neural networks without curse of dimensionality

**Description**: The authors prove that recurrent quantum neural networks can approximate regular state-space systems with approximation error decaying as $1/\sqrt{n}$, where the number of required qubits grows only logarithmically in $1/\varepsilon$ for target accuracy $\varepsilon$, avoiding exponential scaling in dimension.

This contribution was assessed against **2 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

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### 1. Reconfigurable qubit states and quantum trajectories in a synthetic artificial neuron network with a process to direct information generation from co-integrated burst â¦

**URL**: View paper

**Brief Assessment**

Synthetic Neuron Network[44] focuses on experimental hardware implementation of superconductor-ionic memory devices for quantum neuromorphic computing with burst-mode spiking, not theoretical approximation bounds for recurrent quantum neural networks or state-space systems.

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### 2. Quantum Time Dynamics Mediated by the YangâBaxter Equation and Artificial Neural Networks

**URL**: View paper

**Brief Assessment**

Yang-Baxter Dynamics[43] focuses on quantum error mitigation using Yang-Baxter equation for circuit compression in spin chain simulations, not on approximation theory for recurrent quantum neural networks or state-space systems with logarithmic qubit scaling.

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## Contribution 2: Universality of RQNNs with linear readouts for fading memory filters

**Description**: The authors establish that recurrent quantum neural networks with linear readout layers are universal approximators for any causal, time-invariant filter satisfying the fading memory property, matching the expressivity of classical reservoir computing methods.

This contribution was assessed against **5 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

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### 1. An embedding layer-based quantum long short-term memory model with transfer learning for proton exchange membrane fuel stack remaining useful life prediction

**URL**: View paper

**Brief Assessment**

Transfer Learning LSTM[38] focuses on fuel cell remaining useful life prediction using quantum LSTM with transfer learning, not on establishing universal approximation properties of recurrent quantum networks for fading memory filters.

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### 2. Quantum Recurrent Neural Networks for Filtering

**URL**: View paper

**Brief Assessment**

Quantum Filtering Networks[42] focuses on stochastic filtering using Schrödinger wave equations for PDF computation in signal processing, not on universal approximation properties of recurrent quantum networks for fading memory filters with linear readouts.

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### 3. # Quantum Neural Oscillators with Temporal Memory: A Hybrid Framework for Dynamic Information Routing and Attention

**URL**: View paper

**Brief Assessment**

Quantum Neural Oscillators[39] focuses on temporal memory and attention mechanisms using quantum oscillators, not on recurrent quantum neural networks as universal approximators for fading memory filters with linear readouts.

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### 4. Quantum long short-term memory

**URL**: View paper

**Brief Assessment**

Quantum LSTM[40] focuses on implementing LSTM with variational quantum circuits for sequence modeling, not on proving universality properties of recurrent quantum neural networks as approximators for fading memory filters.

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### 5. Enforcing Fading Memory of Noisy Quantum Echo State Networks

**URL**: View paper

**Brief Assessment**

Cannot assess refutation as the candidate paper's full text context is marked 'n/a', preventing comparison of technical content and claims.

## Contribution 3: Novel approximation results for feedforward QNNs and their derivatives

**Description**: The authors develop new approximation error bounds showing that feedforward quantum neural networks can simultaneously approximate target functions and their derivatives, which is essential for analyzing recurrent architectures with feedback loops.

This contribution was assessed against **10 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

### 1. Financial derivafives pricing using quantum neural networks: State-of-the-art

**URL**: View paper

**Brief Assessment**

Financial Derivatives Pricing[32] focuses on quantum neural networks for financial option pricing and computing Greeks (derivatives of option prices). It does not address approximation theory for feedforward QNNs or provide error bounds for approximating functions and their derivatives in the general sense required for recurrent architectures.

### 2. Extended Galerkin neural network approximation of singular variational problems with error control

**URL**: View paper

**Brief Assessment**

Extended Galerkin Network[29] focuses on classical feedforward neural networks for boundary value problems with singular solutions, not quantum neural networks or their derivative approximation properties.

### 3. Solving quantum master equations with deep quantum neural networks

**URL**: View paper

**Brief Assessment**

Deep Quantum Masters[37] focuses on using deep quantum feedforward neural networks to solve quantum master equations for open quantum systems, not on developing approximation error bounds for feedforward QNNs and their derivatives in the context of analyzing recurrent architectures.

### 4. Time series quantum classifiers with amplitude embedding

**URL**: View paper

**Brief Assessment**

Amplitude Embedding Classifiers[36] focuses on time series classification using amplitude embedding techniques for quantum neural networks, not on approximation theory for feedforward QNNs and their derivatives. The candidate addresses practical classification tasks rather than theoretical approximation bounds.

### 5. Physics-informed quantum neural network for solving forward and inverse problems of partial differential equations

**URL**: View paper

**Brief Assessment**

Physics-Informed Quantum[28] focuses on applying QNNs to solve PDEs using physics-informed approaches, not on developing approximation theory for QNN derivatives. The paper mentions QNN universal approximation properties but does not present novel theoretical bounds for approximating functions and their derivatives simultaneously.

### 6. Quantum activation functions for quantum neural networks

**URL**: View paper

**Brief Assessment**

Quantum Activation Functions[35] focuses on implementing activation functions for quantum neural networks through power series approximation, not on approximating feedforward QNN functions and their derivatives for analyzing recurrent architectures with feedback loops.

### 7. Qpde: Quantum neural network based stabilization parameter prediction for numerical solvers for partial differential equations

**URL**: View paper

**Brief Assessment**

Stabilization Parameter Prediction[30] focuses on applying QNNs to predict stabilization parameters for numerical PDE solvers, not on developing approximation theory for feedforward QNNs and their derivatives.

### 8. Realization of a quantum neural network using repeat-until-success circuits in a superconducting quantum processor

**URL**: View paper

**Brief Assessment**

Repeat-Until-Success Circuits[31] focuses on implementing quantum neural networks using repeat-until-success circuits with mid-circuit measurements for non-linear activation functions in superconducting processors. It does not address approximation theory for feedforward QNNs or derivative bounds.

### 9. A derivative-free method for quantum perceptron training in multi-layered neural networks

**URL**: View paper

**Brief Assessment**

Derivative-Free Perceptron[34] focuses on training quantum perceptrons using measurable operators and gradient-free methods, not on approximation error bounds for feedforward QNNs and their derivatives. The candidate does not address function approximation theory or derivative approximation capabilities of quantum neural networks.

### 10. Tensor neural networks for high-dimensional Fokker-Planck equations

**URL**: View paper

**Brief Assessment**

Tensor Fokker-Planck[33] focuses on tensor neural networks for solving Fokker-Planck equations using feedforward networks and radial basis functions, not quantum neural networks or their derivative approximation properties.

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## Appendix: Text Similarity Detection

No high-similarity text segments were detected across any compared papers.

## References


- [0] Feedback-driven recurrent quantum neural network universality View paper
- [1] Feedback-driven quantum reservoir computing for time-series analysis View paper
- [2] Feedback-enhanced quantum reservoir computing with weak measurements View paper
- [3] Optimal training of finitely sampled quantum reservoir computers for forecasting of chaotic dynamics View paper
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