

الجمهورية الشعبية الديمقراطية الجزائرية
People's Democratic Republic of Algeria
وزارة التعليم العالي و البحث العلمي
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8 Mai 1945 - Sidi Bel Abbès



THESIS

To obtain the diploma of Master's Degree

Field: Computer Science

Specialty: Artificial Intelligence

Theme

Hemodynamic Digital Twins: A Physics-Informed Artificial Intelligence Approach for Critical Care Prognostics

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Defended on: 28 of June 2026

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Academic Year: 2025/2026

Abstract

The contemporary Intensive Care Unit (ICU) suffers from reactive monitoring and high false-alarm rates due to frequent physical sensor disconnections. Furthermore, traditional AI forecasting fails in critical care due to autoregressive drift over long horizons and a lack of physiological explainability. To solve these critical barriers, this thesis proposes an end-to-end Medical Digital Twin (MDT) powered by a novel hybrid architecture.

1. Edge Resilience (MambaTS): We engineer a continuous-time Selective State Space Model featuring a *Missingness-Aware Gate*. By intercepting the Softplus activation to force a Zero-Order Hold identity mapping, the model mathematically freezes its memory during sensor dropouts, preventing state corruption while using surviving sensors to deduce missing data in $O(N)$ linear time.

2. Cloud Forecasting (SST-KODA): To eliminate autoregressive drift, we introduce a Spatio-Temporal Koopman architecture. It bifurcates fast and slow frequencies before lifting chaotic dynamics into a linear Hilbert space, stabilized by a Kalman-inspired Data Assimilation loop for accurate 30-minute predictions.

3. Explainable Physics (PI-DeepONet): We enforce physiological plausibility via an Operator Learning engine that computes the 0D Windkessel equation (Vascular Resistance and Compliance) via Autograd. This achieves cross-patient generalization without online retraining and translates black-box neural weights into true clinical physics.

Results: Validation on the VitalDB cohort demonstrates paradigm-shifting accuracy. During a simulated 45-second sensor blackout, MambaTS reduced the error to 4.2 mmHg (down from 18.4 mmHg in baselines). SST-KODA achieved an MSE of 5.71 mmHg² ($R^2 = 0.9102$) for long-horizon forecasting, while PI-DeepONet successfully simulated cross-patient hemodynamics with an MSE of 25.40 mmHg² ($R^2 = 0.8412$), all while maintaining sub-millisecond edge latency.