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МЕТОД ЕМБЕДДИНГУ ДЛЯ АНАЛІЗУ СТАНУ АКУМУЛЯТОРНИХ БАТАРЕЙ

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EMBEDDING METHOD FOR BATTERY STATE ANALYSIS

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Abstract. *This paper presents an embedding-based approach for assessing the state of lithium-ion batteries in a wide range of technical systems, with a particular focus on unmanned platforms. The proposed method introduces an integral battery health vector that combines state of charge, state of health, remaining useful life, and diagnostic features into a multidimensional embedding space. The approach enables clustering, anomaly detection, and short-term forecasting of battery degradation. As a novel extension, the application of the Fast Fourier Transform to temporal analysis of embedding trajectories is proposed, allowing spectral classification and subsequent noise filtering. Application within a multi-agent energy management system for UAVs and UGVs illustrates the practical feasibility of this method.*

Keywords: *lithium-ion battery, embedding vector, state of charge, state of health, remaining useful life, fast fourier transform, multi-agent system.*

Анотація. *У роботі запропоновано підхід на основі ембеддингу для оцінки стану літій-іонних акумуляторів у технічних системах, зокрема безпілотних платформах. Інтегральний вектор, що поєднує показники працездатного стану та діагностичні ознаки, проектується в ембеддинговий простір для кластеризації, виявлення аномалій і прогнозування деградації. Застосування швидкого перетворення Фур'є забезпечує спектральну класифікацію та фільтрацію шумів. Приклад застосування у мультиагентній системі* *енергетичного менеджменту для БпЛА та НРК підтверджує практичну придатність підходу.*

Ключові слова: *літій-іонний акумулятор, ембеддинговий вектор, показники працездатного стану, швидке перетворення Фур'є, мультиагентна система*

Energy autonomy of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) critically depends on reliable battery state assessment. Traditional methods, relying on isolated parameters such as State of Charge (SoC) or internal resistance, are insufficient for comprehensive forecasting and real-time decision-making under dynamic conditions [1]. To overcome these limitations, we propose an integral health vector that unifies key diagnostic indicators with internal resistance, temperature, and impedance features. This vector is projected into an embedding space, where the relative position of each state allows for clustering, anomaly detection, and trend analysis [2]. The embedding representation shifts battery diagnostics from isolated thresholds to a multidimensional geometric interpretation. Each vector point corresponds to a unique technical condition, while distances quantify the similarity of operational states. The method also supports the definition of criticality measures such as the Critical Distance Metric, which enables early identification of transitions toward failure [3]. This compact yet information-rich form serves as an integral index of battery health and facilitates robust decision-making.

To enhance this framework, the application of the Fast Fourier Transform (FFT) to temporal trajectories of the embedding vector is used. This technique separates long-term degradation trends from short-term fluctuations caused by noise or impulsive loads. The resulting spectral signatures enable more robust clustering and classification, while filtering high-frequency noise improves the stability of embedding trajectories. Thus, FFT strengthens both anomaly detection and forecasting. Within a multi-agent energy management system, the embedding representation serves as the core diagnostic layer. Sensor agents collect telemetry, embedder agents project the state vector, classifier agents detect normal or critical states, predictor agents forecast trajectories, and decision agents adjust mission strategies such as rerouting or drone replacement [4]. Operating on embedding vectors rather than raw values makes the system scalable and adaptive. Compared with threshold-based diagnostics, the embedding approach improves interpretability, enables adaptive retraining, and supports real-time use on lightweight edge devices [5]. The integration of FFT extends these benefits, adding spectral indicators that enhance resilience to noise and provide early-warning capabilities. The embedding vector thus functions as a compact, integral index of battery health. Combined with FFT analysis, it supports clustering, anomaly detection, and degradation prediction. This makes the approach suitable for unmanned systems where reliable energy management and adaptive allocation are essential. Future work should expand datasets under realistic conditions and integrate embedding diagnostics with digital twins for dynamic mission-level support.

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ВИКОРИСТАННЯ ЗГОРТКОВОЇ НЕЙРОННОЇ МЕРЕЖІ ДЛЯ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ МОДЕЛЮВАННЯ В CAE - СИСТЕМІ

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