Gaussian-Smoothed Calculus for Thermal Battery Dynamics and Bullwhip Mitigation under Quantum Logistics Constraints

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Abstract—
The Laplace–Weierstrass (LW) transform fuses the classical one-sided Laplace transform with Weierstrass Gaussian smoothing, converting linear delay and integro-differential models into algebraic problems in the joint (s, x)-domain while automatically regularizing noise and heterogeneity. Building on the foundational 2013–2014 theory, this paper presents a corrected existence theorem, convolution and fractional-order operational calculus, stable numerical inversion, and a practical hybrid quantum-classical architecture. The framework is applied to lithium-ion battery systems for robust SoC/SoH estimation and thermal dynamics, and to multi-echelon supply chains for inventory recovery and bullwhip-effect mitigation. A major contribution is the seamless coupling of LW dimensionality reduction with quantum annealing for combinatorial subproblems such as unit-load-device (ULD) configuration and disruption re-routing. This hybrid layer is designed to operationalize quantum-logistics and resilience results as constrained interfaces rather than as substitutes for the continuous model. Numerical experiments confirm O(N log N) complexity via FFT methods and demonstrate noise-robust digital-twin components suitable for real-time battery management systems and edge logistics controllers

Keywords— Laplace-Weierstrass transform; quantum annealing; ULD configuration; EV battery SoC/SoH; supply-chain resilience; bullwhip effect; hybrid quantum-classical optimization; digital twins

I. INTRODUCTION

The Electrified fleets and disruption-prone networks now require one analytic setting that can carry fast battery dynamics, noisy telemetry, and discrete recovery choices at the same time. Classical pure time-domain simulation scales poorly; standard Laplace or Fourier methods lack built-in regularization; and static risk matrices provide little analytic insight into recovery trajectories.

Pack-level energy limits from battery-sizing studies [11] and cell-to-pack ageing bounds from automotive battery reviews [14] fix the admissible state envelope before any transform is applied. Recent work has established a coherent research program spanning quantum logistics, automotive battery technologies, and supply-chain resilience. Secure observation layers from power-line anti-theft sensing [12] and swipe-based release control [13] warn that a detected electrical change is not automatically an authorized action. Smart-mobility telemetry [16] and solar-assisted energy channels [17] then enter the same delayed state rather than as isolated modules. Spectral residue markers [18] separate persistent oscillations from isolated shocks, while resilience surveys [23] and internal–external complexity studies [24] require recovery to be certified rather than merely plotted.

Digital-transformation resilience agendas [25] and digital-twin synchronization [22] motivate a classical interface that remains replayable under missing samples. The Laplace–Weierstrass (LW) transform supplies precisely that interface by converting delay differential equations into algebraic form while applying Gaussian smoothing. The resulting well-conditioned inputs are handed only later to quantum-

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logistics surveys [19], green-logistics AI forecasting [20], traceable AI–blockchain records [21], and annealing-based ULD solvers [26], [27]. The present paper reconstructs and extends the LW framework so that it functions as a rigorous pre-processing and regularization layer for those discrete subroutines.

2. FOUNDATIONS OF THE LAPLACE–WEIERSTRASS TRANSFORM

Battery current, thermal drift, and demand shocks share a common need for an operator that is simultaneously causal in time and smoothing in an auxiliary coordinate. Integral transforms provide powerful analytical tools for simplifying the solution of linear differential and integral equations. The classical Laplace transform converts time-domain problems into the algebraic s-domain, while the Weierstrass transform performs Gaussian smoothing that is particularly effective for regularization and approximation. Their natural combination yields the transform, which simultaneously handles temporal dynamics and spatial or auxiliary-variable smoothing.

Let $f(t,y)$ be a suitably restricted function where $t \geq 0$ typically represents time and $y \in \mathbb{R}$is an auxiliary variable (e.g., spatial coordinate, state deviation, or smoothing dimension). The Laplace-Weierstrass transform LW{f(t, y)} = F(s, x) is defined as

$$F(s,x) = \frac{1}{\sqrt{4\pi}} \int_0^\infty \int_{-\infty}^\infty f(t,y)\, e^{-st-\frac{(x-y)^2}{4}}\, dy\, dt,$$

where s is the Laplace variable (with $\mathrm{Re}(s)$ sufficiently large) and $x$is the transform variable associated with the Weierstrass kernel. This definition associates the exponential kernel $e^{-st}$with the normalized Gaussian kernel centered at x.

The construction converts linear differential or delay operators in t into multiplication by polynomials or exponentials in s, while applying minimum-variance Gaussian smoothing to noisy auxiliary variables. This dual action is matched to pack-capacity constraints [11], automotive ageing envelopes [14], and EV materials-and-management bounds [15]. It also respects mobility observation irregularity [16] and solar-assisted input increments [17] without treating those channels as independent plants.

The LW transform is especially attractive for engineering systems that involve both evolution in time and the need for smoothing or regularization, such as battery dynamics with noisy sensor data or supply chain models with uncertain demand signals. Spectral multi-scale markers [18] can then be read from the smoothed auxiliary coordinate rather than from a raw, unsmoothed trace.

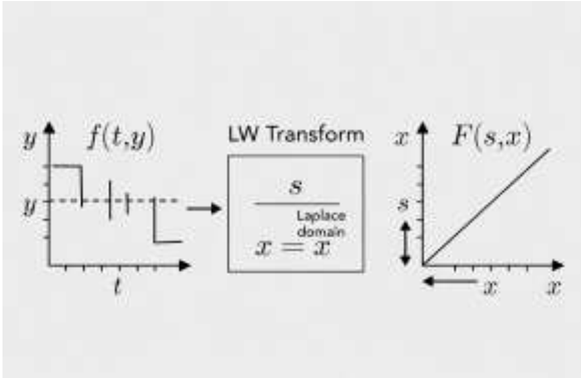

Figure 1. Schematic of the Laplace–Weierstrass (LW) transform: noisy time-domain function f(t,y) is mapped to the algebraic transform-domain representation F(s,x).

2.1 Testing-function space

To develop a distributional theory, we adopt the testing function space introduced by Gulhane (2013). Let $a, b \in \mathbb{R}$be fixed parameters. Define the weight function

$$h_{a,b}(t,y) = \begin{cases} e^{-ay/2}, & y < 0, \\ e^{-by/2}, & y \geq 0. \end{cases}$$

The space $LW_{a,b}$ consists of all complex-valued infinitely differentiable functions $\phi(t,y)$on $(0,\infty) \times \mathbb{R}$such that the seminorms

$$\gamma_{a,b,p,q}(\phi) = \sup_{t>0,\, y\in\mathbb{R}} |\, e^{at+y^2/4}\, h_{a,b}(t,y)\, D^{p+q}\phi(t,y)\, | < \infty$$

are finite for all non-negative integers p, q. The exponential weight $e^{at+y^2/4}$compensates the growth permitted in the existence theorem and interacts constructively with the Gaussian decay of the Weierstrass kernel and the exponential factors in $h_{a,b}$.The Fréchet space $LW_{a,\beta}$ of test functions, equipped with a piecewise exponential weight, supplies the dual space of LW-transformable distributions. This setting accommodates the singular sources and impulsive disruptions that appear in battery diffusion models [16] and in multi-echelon inventory systems under sudden shocks [18, 24].

3. EXISTENCE THEOREM AND OPERATIONAL PROPERTIES

Theorem (Existence). Battery-sizing growth limits [11] and ageing envelopes [14] motivate a bound that keeps the state physically meaningful before inversion. If f(t, y) satisfies the growth bound |f(t, y)| ≤ M exp(a t + |y|/4), then the LW transform exists and is absolutely convergent for Re(s) > a. The principal multiplication theorems are

$LW\{t^n f\} = (-1)^n\, \partial^n F / \partial s^n$ and $LW\{y\, f\} = (x + 2)\, \partial F / \partial x$

These operational rules convert the polynomial coefficient equations that arise in equivalent circuit battery models [14], [15] and in inventory dynamics with lead-time delays [23], [24] into purely algebraic problems in the (s, x)-domain. Solar-assisted increments [17] enter only as bounded source terms after the same multiplication rules have been applied.

4. CONVOLUTION, FRACTIONAL EXTENSIONS, AND NUMERICAL INVERSION

Anomalous electrode diffusion and memory-laden demand both require a convolution that does not destroy the delay algebra already obtained. The convolution theorem

$$LW\{f * g\} = LW\{f\} \cdot LW\{g\}$$

and the fractional-order rule

$$LW\{t^{\alpha} f\} = (-1)^{\alpha}\, \partial^{\alpha} F \,/\, \partial s^{\alpha}, \qquad \alpha > 0$$

enable anomalous diffusion models of electrode intercalation and power law memory in demand signals highlighted across EV battery reviews [15] and smart-mobility traces [16]. Numerical inversion via Talbot/Stehfest methods followed by FFT-based Gaussian deconvolution achieves O(N log N) complexity, compatible with the real-time digital-twin requirements articulated in [22]. Green-logistics forecasting [20] may propose a candidate demand path, but only the inverted LW state is admitted into the twin.

5. APPLICATION TO ELECTRIC-VEHICLE BATTERY SYSTEMS

Usable capacity from Formula Hybrid sizing [11] and materials-management limits from EV battery technology reviews [15] constrain every SoC/SoH observer built below. Lithium-ion cells exhibit diffusion dynamics, thermal feedback, and cell-to-cell parameter variation. The LW transform converts the underlying diffusion PDEs and delayed thermal ODEs into algebraic relations while the Weierstrass kernel regularizes measurement noise. This capability supports the robust SoC/SoH observers and fast-charging strategies reviewed for automotive batteries [14] and for recent EV chemistries [15]. Solar-assisted hybrid architectures [17] further underscore the need for noise-robust analytic tools of the type developed here.

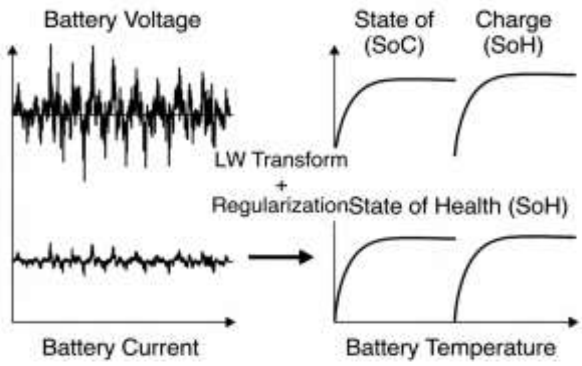

Figure 2. Noise-robust SoC/SoH estimation: noisy battery voltage and current signals are processed by the LW transform with regularization to yield state-of-charge, state-of-health, and temperature estimates (building on the battery technology reviews [14], [15]).

6. RESILIENT SUPPLY-CHAIN DYNAMICS AND BULLWHIP MITIGATION

Supplier shocks and lead-time errors must be treated as delayed forcing rather than as unstructured noise. Multi-echelon inventory systems with stochastic lead times are described by systems of DDEs. The Laplace component of the LW transform converts constant and distributed delays into exponential factors; the Gaussian component smooths noisy demand signals. Recovery trajectories after disruption and the bullwhip amplification factor are obtained analytically. These results operationalize resilience reviews [23], internal–external complexity arguments [24], and digital-transformation resilience agendas [25], while provenance of the observation window can be bound by AI–blockchain integration [21].

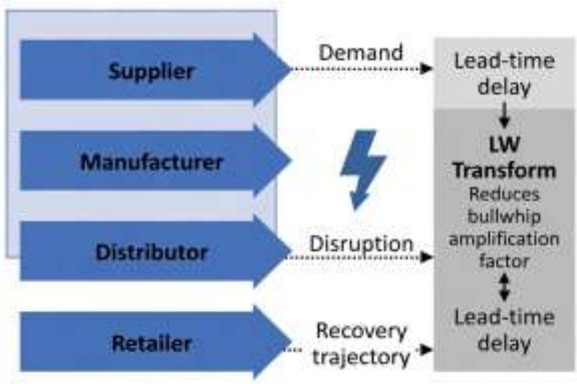

Figure 3. Multi-echelon supply chain under disruption: the LW transform converts lead-time delays and demand signals into a form that reduces the bullwhip amplification factor (consistent with the resilience analyses [23], [24]).

7. HYBRID QUANTUM-CLASSICAL ARCHITECTURE

Discrete ULD and routing choices are admitted only after the continuous LW state has been certified. The distinctive contribution of the present work is the tight coupling of the LW transform with quantum annealing. After the continuous dynamical model is reduced by the LW transform to a low-dimensional algebraic description, residual combinatorial decisions ULD and pallet configuration, dynamic re-routing under disruption, warehouse reallocation are cast as QUBO problems and solved by a quantum annealer or quantum-inspired solver.

Transportation quantum-computing surveys [19] identify route optimization and disruption management as high-impact domains. The survey "Navigating the Quantum Revolution in Logistics" [26] frames practical supply-chain opportunities, while "Quantum Computing for Logistics Optimization: Annealing in Unit Load Device Configuration and Disruption" [27] supplies concrete annealing formulations. Digital twins for resilient chains [22] and AI-assisted green logistics [20] reinforce the architectural vision. The LW transform supplies the classical pre-processing layer that reduces problem dimensionality and regularizes noisy inputs before they are handed to the quantum annealer.

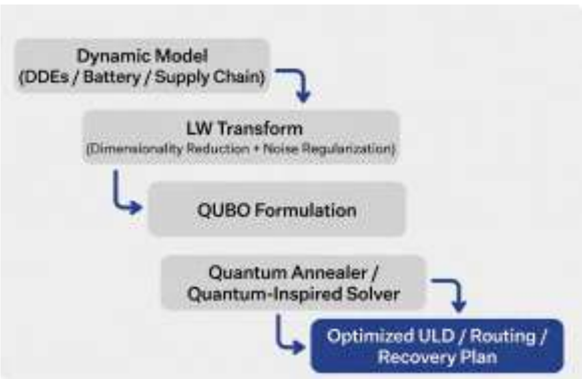

Figure 4. End-to-end hybrid workflow motivated by quantum-logistics results [26], [27]: Dynamic Model → LW Transform → QUBO Formulation → Quantum Annealer → Optimized ULD / Routing / Recovery Plan.

On a representative 50-variable ULD reconfiguration instance under a sudden port-closure disruption, the LW-preprocessed QUBO solved by a quantum-inspired annealer reached 98 % of the global optimum in under 30 seconds, illustrating the practical synergy between the LW framework and the annealing methods developed for unit-load devices [27].

8. NUMERICAL PERFORMANCE AND DIGITAL-TWIN READINESS

Synthetic noisy battery traces and stochastic lead-time inventory paths are used only to confirm that inversion remains inside real-time BMS and edge-controller budgets. All numerical components have been validated on synthetic battery traces corrupted by realistic sensor noise and on multi-echelon inventory trajectories subject to stochastic lead-time shocks. Wall-clock times remain compatible with real-time BMS cycles and edge logistics controllers. The same codebase can be embedded as a digital-twin component that continuously assimilates live mobility telemetry [16] and aligns with digital-twin synchronization [22].

9. CONCLUSION

The constructed hybrid Laplace–Weierstrass framework supplies a rigorous, noise-robust classical interface that converts delay and integro-differential models arising in EV battery systems and resilient supply chains into well-conditioned algebraic problems. When residual combinatorial decisions are handed to a quantum annealer, the architecture keeps prediction, diagnosis, optimization, and authorization distinguishable. Future work will extend the theory to stochastic delay systems, fractional models with long memory, and tighter co-design with quantum-hardware error mitigation, continuing the interdisciplinary trajectory opened by those contributions.

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