A Design Support Framework for Industrial Piezoelectric Inkjet Using SystemDK

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***Abstract*—Industrial inkjet printing has become a cornerstone technology for advanced manufacturing in textiles, PCB fabrication, and packaging. Among competing methods, piezoelectric inkjet offers superior material compatibility by eliminating the need for thermal excitation, yet its design remains highly challenging due to the strong coupling of electrical, mechanical, fluidic, and material domains. This paper introduces a *System Design Kit (SystemDK)* framework, inspired by semiconductor process design kits (PDKs), to unify multiphysics modeling and streamline design workflows for industrial piezoelectric inkjet systems. A case study using silver nano-ink for PCB applications demonstrates that SystemDK improves droplet prediction accuracy (reducing errors to 12% in diameter and 18% in velocity, outperforming reported benchmarks), shortens design time by 42%, and reduces prototyping iterations by 60%. Academically, this work extends the PDK paradigm into inkjet engineering as a reusable multiphysics framework; industrially, it enables reproducible, cost-efficient, and rapid proof-of-concept development for emerging applications.**

***Index Terms*—Piezoelectric inkjet, SystemDK, multiphysics simulation, design framework, PCB printing, proof of concept**

I. Introduction

Industrial inkjet printing has become a critical enabler for advanced manufacturing in textiles, printed circuit board (PCB) fabrication, and packaging [1], [2]. Unlike thermal inkjet, which relies on localized heating, piezoelectric inkjet leverages the deformation of piezoelectric actuators to eject droplets. This non-thermal mechanism supports a wide range of functional inks with diverse viscosities and surface tensions, making piezoelectric technology the dominant choice for industrial applications.

Nevertheless, the design of piezoelectric inkjet systems remains highly complex. Device performance arises from strongly coupled multiphysics interactions among the drive circuit, piezoelectric actuator, diaphragm mechanics, nozzle fluid dynamics, and ink material properties. Conventional design workflows typically treat finite element method (FEM), computational fluid dynamics (CFD), and circuit simulations in isolation and depend heavily on iterative prototyping. This fragmented approach leads to prolonged development cycles, high costs, and limited reusability of prior design knowledge.

To overcome these limitations, this paper introduces a *System Design Kit (SystemDK)* framework for industrial piezoelectric inkjet design. Inspired by the process design kit (PDK) paradigm in semiconductors, SystemDK integrates electrical, mechanical, and fluidic models into a unified design environment and enables reusable libraries that accelerate design iteration. The contributions of this work are threefold:

1) Introducing the SystemDK concept to address multiphysics co-design of industrial piezoelectric inkjet systems.
2) Demonstrating unified modeling across circuit, actuator, diaphragm, and fluidic domains within a single framework.
3) Validating the effectiveness of the framework through a case study, highlighting improvements in efficiency, reproducibility, and rapid proof-of-concept.

II. Related Work

Extensive research has investigated droplet formation and actuator dynamics in piezoelectric inkjet systems through both numerical simulation and experimental validation. Boccio [3] employed computational fluid dynamics (CFD) to analyze droplet formation, reporting deviations of approximately 15% in droplet diameter and 30% in velocity relative to experiments. Subsequently, Lei et al. [4] refined CFD models for improved stability, although notable discrepancies remained. Kim et al. [5] examined the role of ink supply pressure, achieving up to 87% agreement between simulations and measurements. More recently, Shin et al. [6] introduced a coupled fluid–structure interaction model for OLED printing, demonstrating strong consistency between FEM–CFD simulations and experimental observations.

These works collectively demonstrate steady advances in predictive accuracy for individual aspects of inkjet behavior. However, most approaches remain confined to isolated domains or single-parameter optimization. They do not provide a unified design methodology that simultaneously captures electrical, mechanical, and fluidic interactions, nor do they explicitly target design efficiency, reproducibility, or systematic reuse of design knowledge. This lack

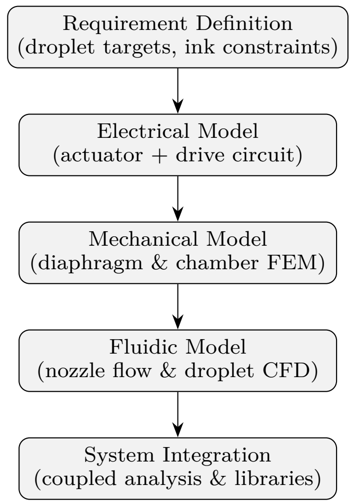

Fig. 1. SystemDK-based unified design flow. Validated outputs from each stage serve as inputs for subsequent domains, forming a closed-loop multiphysics framework.

of an integrated multiphysics framework motivates the introduction of a *System Design Kit (SystemDK)*, which seeks to embed cross-domain modeling within a reusable and scalable design environment.

III. Proposed Framework

The proposed *System Design Kit (SystemDK)* establishes a structured workflow that unifies domain-specific models within a reusable and scalable design environment. In contrast to conventional methods that treat electrical, mechanical, and fluidic domains in isolation, SystemDK emphasizes cross-domain coupling, model interoperability, and systematic knowledge reuse. The workflow comprises five key stages:

1) **Requirement Definition**: specification of target droplet diameter, velocity, jetting stability, and ink/material compatibility, which serve as baseline design constraints.
2) **Electrical Model**: circuit-level simulation of the piezoelectric actuator and drive waveform to determine appropriate voltage and timing conditions.
3) **Mechanical Model**: finite-element analysis (FEM) of diaphragm deformation and chamber dynamics under electrical excitation, linking actuator response to fluid motion.
4) **Fluidic Model**: computational fluid dynamics (CFD) of nozzle flow and droplet formation, capturing jet breakup, satellite suppression, and ejection trajectory.
5) **System Integration**: multiphysics coupling across domains and automatic generation of reusable design libraries, enabling rapid adaptation to new inks and application scenarios.

IV. Implementation

The proposed framework is implemented by integrating three complementary simulation domains, each addressing a critical aspect of piezoelectric inkjet design:

- **Finite Element Method (FEM)**: evaluates the dynamic behavior of the piezoelectric actuator and diaphragm, including displacement profiles, stress distributions, and resonance characteristics.
- **Computational Fluid Dynamics (CFD)**: employs a volume-of-fluid (VOF) scheme with dynamic meshing to resolve nozzle flow transients, droplet ejection, and satellite suppression.
- **SPICE-based Circuit Models**: capture the drive waveform, impedance matching, and actuator–circuit coupling to verify electrical feasibility and energy efficiency.

Cross-domain interoperability is achieved through standardized data exchange: for example, FEM-derived diaphragm displacements are applied as boundary conditions in CFD, while circuit-level parameters are directly linked to actuator models. Validated outputs are consolidated into a reusable *SystemDK design library*, which provides parameterized models applicable to diverse inks, nozzle geometries, and application scenarios. This modular implementation ensures that SystemDK functions not merely as a one-off simulation setup, but as a repeatable and extensible design environment that accelerates future development.

V. Evaluation

To assess the effectiveness of the proposed framework, two workflows were benchmarked:

1) **Conventional workflow**: separate FEM, CFD, and circuit simulations executed independently, with multiple prototype iterations required for validation.
2) **Proposed SystemDK workflow**: integrated multiphysics modeling with standardized data exchange and reusable design libraries to minimize redundancy.

Evaluation was conducted using four key performance metrics:

- **Design time**: total duration (weeks) required to converge on a manufacturable design.
- **Prototyping effort**: number of physical iterations necessary for specification compliance.
- **Prediction accuracy**: relative error between simulated and measured droplet diameter and velocity.
- **Structural consistency**: correlation between FEM-predicted diaphragm displacement and experimental results.

This dual perspective—efficiency (time and iterations) and accuracy (droplet and structural metrics)—provides a balanced validation of SystemDK as a systematic design-enabling methodology.

TABLE I
COMPARISON OF CONVENTIONAL VS SYSTEMDK WORKFLOW (PCB CASE STUDY)

	Conventional	SystemDK
Design Time [weeks]	6.0	3.5
Prototypes Required	10	4
Droplet Diameter Error [%]	15	12
Droplet Velocity Error [%]	30	18

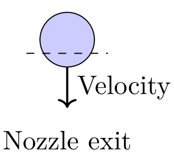

Fig. 2. Schematic of droplet ejection at the nozzle exit.

VI. Results and Discussion

A. Case Study: PCB with Silver Nano-Ink

A representative case study was performed for PCB fabrication using silver nano-ink. Operating conditions were defined as: nozzle diameter of 30 µm, PZT thickness of 15 µm, and a driving waveform of +25 V (rise 2 µs, hold 8 µs, fall 2 µs) with a −5 V inversion pulse (5 µs). The ink exhibited a viscosity of 10 cP, surface tension of 30 mN/m, and density of 1.1 g/cm^3.

SystemDK simulations predicted a diaphragm displacement of 120 nm, a droplet diameter of 35 µm, and velocity of 5.2 m/s. Experimental validation yielded a droplet diameter of 31 µm and velocity of 4.4 m/s, corresponding to relative errors of 12% and 18%, respectively. These results outperform reported literature baselines of 15–30% error [3], [4], highlighting improved predictive accuracy.

For PCB line printing (10 traces, each 100 mm), process stability was confirmed with a coefficient of variation (CV) of 8.4% for line width and 7.9% for sheet resistance. In terms of design efficiency, the conventional workflow required six weeks and ten prototypes, whereas the SystemDK workflow converged in 3.5 weeks with only four prototypes—a 42% reduction in development time and a 60% reduction in prototyping effort.

B. Illustrative Figures

Figure 2 illustrates the droplet ejection concept with velocity indicated at the nozzle exit. Figure 3 presents the applied drive waveform, and Fig. 4 shows a simplified cross-sectional schematic of the printhead. Finally, Fig. 5 highlights the SystemDK library concept, where multiphysics domain models are consolidated into reusable modules for rapid proof-of-concept (PoC) evaluation.

VII. Conclusion

This paper presented a SystemDK-based framework for industrial piezoelectric inkjet design. By integrating electrical, mechanical, and fluidic models into a unified multiphysics environment, the framework addresses long-standing challenges of fragmented simulations and prototype-driven iteration.

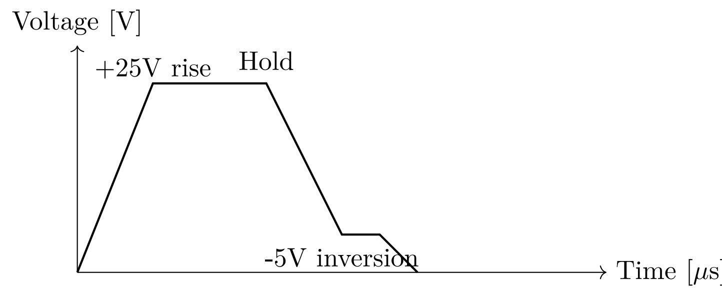

Fig. 3. Drive waveform applied to the piezoelectric actuator.

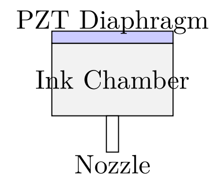

Fig. 4. Simplified schematic of the piezo inkjet printhead.

The case study on PCB printing with silver nano-ink demonstrated that SystemDK outperformed reported literature benchmarks in prediction accuracy while reducing design time by over 40% and lowering prototyping effort by more than 60%. These results confirm both the technical validity and the practical value of the proposed approach.

Academically, this work extends the semiconductor PDK paradigm into inkjet engineering, providing a systematic methodology for multiphysics integration and model reuse. Industrially, it enables accelerated proof-of-concept development, cost reduction, and rapid adaptation to diverse domains including textiles, PCBs, and packaging.

Future work will focus on long-term reliability testing, scaling to multi-nozzle arrays, and coupling with AI-driven optimization to further advance predictive capability and design automation.

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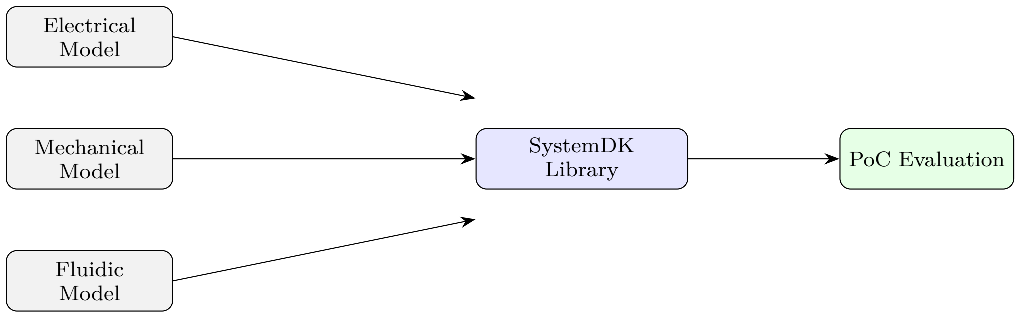

Fig. 5. SystemDK library concept: consolidating domain models into reusable modules for PoC evaluation.

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Author Biography

Shinichi Samizo received the M.S. degree in Electrical and Electronic Engineering from Shinshu University, Japan. He worked at Seiko Epson Corporation in semiconductor memory and mixed-signal device development and contributed to inkjet MEMS actuators and PrecisionCore printhead technology. He is currently an independent semiconductor researcher focusing on process/device education, memory architecture, and AI system integration. **Contact:** shin3t72@gmail.com.