

# Lead-free Bio-Inkjet Printing with Bulk KNN Actuators and AITL-based Adaptive Control

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**Abstract**—This paper proposes a biocompatible inkjet printing architecture based on lead-free piezoelectric actuators, specifically bulk KNN ( $(\text{K},\text{Na})\text{NbO}_3$ ), combined with chip-on-film (COF) driver ICs, silicon cavity integration, and an AITL (Adaptive Intelligent Three-Layer) supervisory control framework. Unlike conventional PZT-driven industrial heads, the KNN approach supports biocompatibility and Pb-free compliance, while moderate performance (3–5 pL droplets,  $10^6$  shots,  $\pm 50$  V operation) satisfies bioprinting needs. Beyond actuation, the electromechanical response of KNN is leveraged for *self-diagnosis*: detecting missing droplets and estimating ink viscosity. This diagnostic data feeds into an AITL architecture—an inner PID loop for real-time stability, an FSM layer for mode transitions and compensation, and an LLM-driven supervisory layer for adaptive redesign of control rules. We present the architecture, process flow, and representative biomedical applications, highlighting the potential of KNN as both actuator and sensor.

## I. INTRODUCTION

Inkjet printing has become a versatile technology in both industrial and consumer applications, with piezoelectric lead zirconate titanate (PZT) actuators serving as the dominant driver mechanism. Despite extensive research on lead-free piezoelectrics such as  $(\text{K},\text{Na})\text{NbO}_3$  (KNN) and  $\text{Bi}_{0.5}\text{Na}_{0.5}\text{TiO}_3$  (BNT), these alternatives have not replaced PZT in mainstream printing due to insufficient compatibility in key metrics such as piezoelectric coefficient  $d_{33}$ , long-term durability, and cost-effective manufacturing.

In biomedical applications, however, the design requirements differ fundamentally. Rather than extreme durability and maximum actuation strength, biocompatibility, chemical safety, and moderate performance are the primary needs. Typical bio-printing tasks—including cell patterning, protein array generation, and hydrogel dispensing—require droplet volumes in the range of 1–10 pL and endurance on the order of  $10^6$  shots, which are significantly less demanding than industrial printing standards.

This work therefore explores a Bio-Inkjet (Bio-IJ) architecture based on bulk KNN actuators, combined with chip-on-film (COF) driver integration and silicon cavity bonding. By tailoring the system to biomedical rather than industrial requirements, the proposed approach provides a feasible lead-free alternative that aligns with environmental regulations and biological safety.

## II. BACKGROUND: PB-FREE PIEZOELECTRICS

Research on lead-free piezoelectrics has been pursued for more than two decades as part of global efforts to replace lead zirconate titanate (PZT) with environmentally benign alternatives. Among the most prominent candidates are  $(\text{K},\text{Na})\text{NbO}_3$  (KNN),  $\text{Bi}_{0.5}\text{Na}_{0.5}\text{TiO}_3$  (BNT), and Sc-doped AlN (ScAlN).

KNN typically exhibits a piezoelectric coefficient  $d_{33}$  in the range of 150–250 pm/V, with optimized compositions reaching up to 300–400 pm/V, and a Curie temperature exceeding 400 °C. These properties make it suitable for moderate-displacement actuators. In contrast, ScAlN provides a more modest  $d_{33}$  of 20–30 pm/V, but its excellent CMOS compatibility and feasibility for thin-film MEMS integration have positioned it as an attractive material for micro-scale devices. BNT and related systems have also been investigated, though issues such as depolarization and processing complexity have limited their adoption.

Despite these advances, industrial printing applications have not embraced Pb-free piezoelectrics. The primary obstacle has been the expectation of *full PZT compatibility*—requiring identical performance in terms of strain output, durability over  $10^9$  cycles, and manufacturing cost. Such stringent requirements exceed the current capabilities of KNN, BNT, or ScAlN.

In biomedical printing, however, these limitations are less critical. Because the performance demands are moderate and biocompatibility is a non-negotiable requirement, Pb-free piezoelectrics can be reconsidered as practical actuator materials for Bio-Inkjet systems.

## III. PROPOSED ARCHITECTURE

The proposed Bio-Inkjet (Bio-IJ) actuator system is designed to balance biocompatibility, manufacturability, and sufficient actuation performance for biomedical applications. Its main components are as follows:

- **Bulk KNN multilayer stack actuator:** A 200–500  $\mu\text{m}$  thick piezoelectric stack providing moderate displacement suitable for picoliter-scale droplet ejection.
- **COF driver IC:** A chip-on-film high-voltage driver with 16–32 channels, operating at up to  $\pm 50$  V, and incorporating waveform RAM with SPI control for flexible pulse shaping.

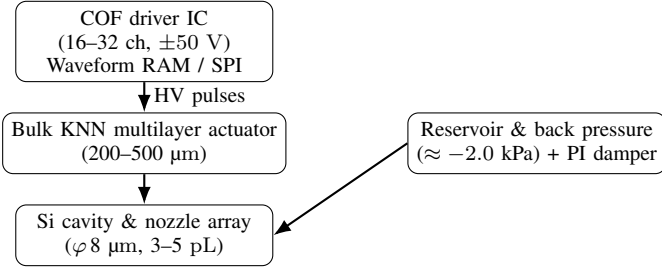


Fig. 1. System architecture of the proposed Bio-Inkjet (Bio-IJ). A bulk KNN actuator, COF high-voltage driver, silicon cavity/nozzles, and fluidics (back-pressure with PI damper) are integrated.

Back pressure  $\approx -2.0$  kPa;  
PI membrane damper; Supply

Target: 3-5 pL droplets;  
 $\sim 10^6$  shots class

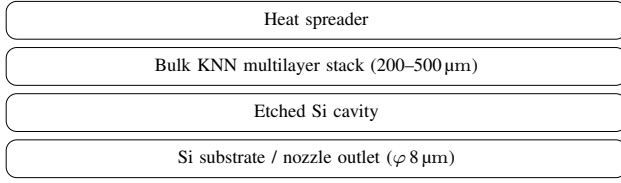


Fig. 2. Cross-sectional schematic of the Bio-IJ printhead. The KNN stack is bonded to a silicon cavity with  $\phi 8 \mu\text{m}$  nozzles; fluidics provide back-pressure stabilization and damping.

- **Si cavity and nozzle array:** A silicon-etched cavity directly bonded to the actuator, with nozzles of  $\phi 8 \mu\text{m}$  diameter producing droplets in the 3-5 pL range.
- **Reservoir and back pressure control:** A fluidic supply stabilized at approximately -2.0 kPa using a PID-controlled regulator to ensure consistent meniscus positioning.
- **PI membrane damper:** A polyimide-based damping layer integrated in the reservoir to suppress pressure fluctuations and prevent satellite droplets.

The associated *process flow* begins with fabrication of the bulk KNN stack and electrode finishing, followed by terminal cutting and COF assembly. The actuator is then mounted with a heat spreader for thermal management and finally bonded to the silicon cavity structure, resulting in an integrated Bio-IJ printhead module.

#### A. Self-Diagnosis and AITL Control

The electromechanical response of the bulk KNN actuator can be exploited for self-diagnosis and adaptive control. Surrogate signals derived from drive current and charge increments correlate with droplet volume and viscosity, enabling online monitoring.

Two representative strategies are highlighted:

- **Self-diagnosis:** Detecting missing droplets by charge/displacement thresholds, estimating viscosity from relaxation dynamics.
- **Adaptive control:** Updating PID gains and FSM transitions in real time based on surrogate measurements, while keeping safety constraints (drive voltage  $\leq \pm 50$  V).

Detailed mathematical models, including recursive least squares (RLS) identification, MIT-rule adaptation, and viscosity mapping, are provided in the Appendix.

## IV. APPLICATIONS

The proposed Bio-Inkjet architecture enables several key biomedical applications in which moderate actuation performance, precise droplet control, and biocompatibility are prioritized over extreme durability:

- **Cell patterning:** Controlled deposition of living cells into predefined patterns for tissue engineering and regenerative medicine. Gentle actuation and droplet volumes of 1-10 pL support high cell viability, with survival rates above 80% reported under comparable shear stress conditions.
- **Protein and DNA microarrays:** Picoliter-scale dispensing of biomolecules onto functionalized substrates for high-throughput screening, diagnostics, and drug discovery. The ability to generate uniform, sub-100  $\mu\text{m}$  spots is critical for assay reproducibility.
- **Hydrogel 3D printing:** Layer-by-layer deposition of bio-compatible hydrogels, followed by UV or thermal curing, to fabricate soft scaffolds for cell culture and organ-on-chip platforms. Precise droplet placement ensures structural fidelity and material homogeneity.

These use cases demonstrate that the moderate performance of bulk KNN actuators—picoliter droplet generation at voltages below  $\pm 50$  V—is sufficient to meet biomedical requirements. Here, droplet volume control, biocompatibility, and integration with fluidic handling systems are far more critical than the billion-cycle endurance demanded in industrial printing.

## V. CONCLUSION

This paper has proposed a Bio-Inkjet (Bio-IJ) architecture based on bulk KNN actuators as a lead-free alternative to conventional PZT-based printheads. By combining multilayer KNN stacks, COF driver ICs, and silicon cavity integration, the system achieves picoliter-scale droplet generation under moderate voltages while ensuring material biocompatibility.

Unlike industrial printing, where full PZT compatibility in terms of maximum  $d_{33}$ , billion-cycle endurance, and cost efficiency is required, biomedical printing places emphasis on safety, controlled droplet volume, and operational reliability over shorter lifetimes. The proposed approach aligns well with these requirements, providing sufficient performance for applications such as cell patterning, protein microarrays, and hydrogel 3D fabrication.

These findings highlight bulk KNN as a practical foundation for standardizing lead-free Bio-IJ systems in research, clinical, and educational domains. Future work will involve experimental validation of droplet formation, long-term reliability testing under bio-relevant conditions, and system integration with existing bioprinting workflows.

## APPENDIX A

### AITL CONTROL DERIVATIONS

#### A. Surrogate Sensing and Plant Model

During a drive pulse  $u_k$ , the KNN stack current  $i(t)$  and charge  $q(t) = \int i(t)dt$  define surrogate features:

$$y_k \triangleq \alpha_1 q_k^{\text{peak}} + \alpha_2 \Delta q_k + \alpha_3 t_{r,k}, \quad (1)$$

with calibration coefficients  $\alpha_i$ .

#### B. Inner-Loop Dynamics

We adopt a discrete 2nd-order model:

$$y_{k+1} = a_1(\eta)y_k + a_2(\eta)y_{k-1} + b_0(\eta)u_k + b_1(\eta)u_{k-1} + d_k, \quad (2)$$

where viscosity  $\eta$  influences  $\{a_i, b_i\}$ .

#### C. Recursive Least Squares (RLS)

The parameter update follows:

$$\theta_k = \theta_{k-1} + K_k(y_k - \phi_k^\top \theta_{k-1}), \quad (3)$$

$$K_k = \frac{P_{k-1}\phi_k}{\lambda + \phi_k^\top P_{k-1}\phi_k}, \quad (4)$$

$$P_k = \lambda^{-1}(P_{k-1} - K_k\phi_k^\top P_{k-1}), \quad (5)$$

with forgetting factor  $\lambda \in (0, 1]$ .

#### D. Adaptive PID Examples

##### IMC-PID Retuning:

$$K_p = \frac{\tau + \theta}{K(\lambda + \theta)}, \quad K_i = \frac{K_p}{\tau + \theta}, \quad K_d = \frac{\tau\theta}{2(\tau + \theta)}. \quad (6)$$

##### MIT Rule:

$$\theta_{k+1} = \theta_k - \Gamma\psi_k e_k, \quad \psi_k = \frac{\partial \hat{y}_k}{\partial \theta}. \quad (7)$$

## REFERENCES

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## AUTHOR BIOGRAPHY

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