Real-time Fitting and Materials Characterization in Band-Excitation Piezoresponse Force Microscopy

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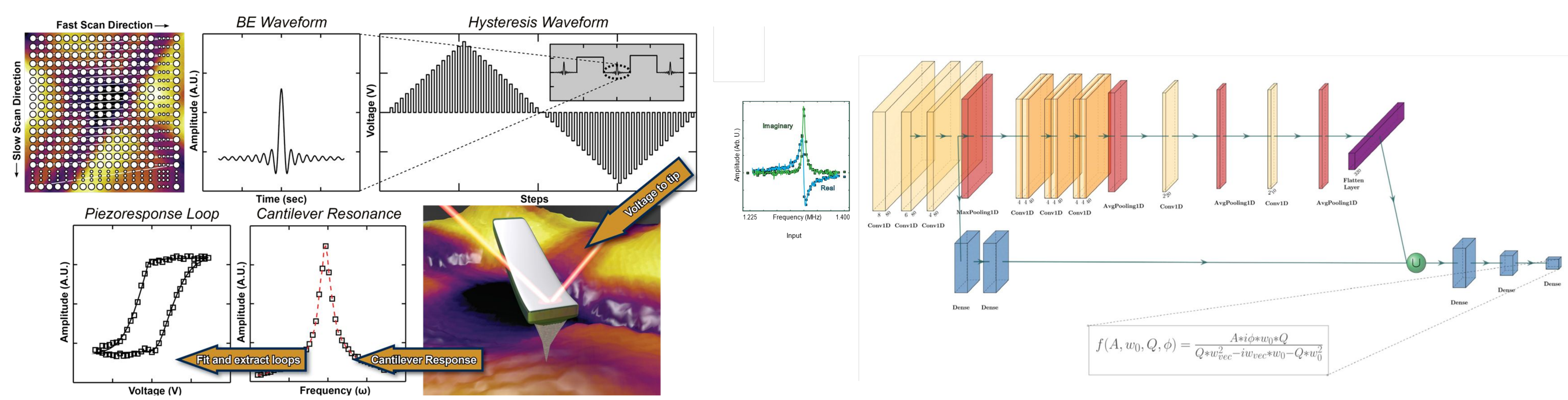
Abstract

Increased development and utilization of multimodal scanning probe microscopy (SPM) and spectroscopy techniques have led to an orders-of-magnitude increase in the volume, velocity, and variety of collected data. While larger datasets have certain advantages, practical challenges arise from their increased complexity including the extraction and analysis of actionable scientific information. In recent years, there has been an increase in the application of machine and deep learning techniques that use batching and stochastic methods to regularize statistical models to execute functions or aid in scientific discovery and interpretation. While this powerful method has been applied in a variety of imaging systems (e.g., SPM, electron microscopy, etc.), simplistic analysis alone takes on the order of weeks to months due to scheduling and IO overhead imposed by GPU and CPU based systems which limits streaming inference rates to speeds above 50ms. This latency precludes the possibility of real-time analysis in SPM techniques such as band-excitation piezoresponse force spectroscopy (BE PFM), where typical measurements of cantilever resonance occur at 64Hz.

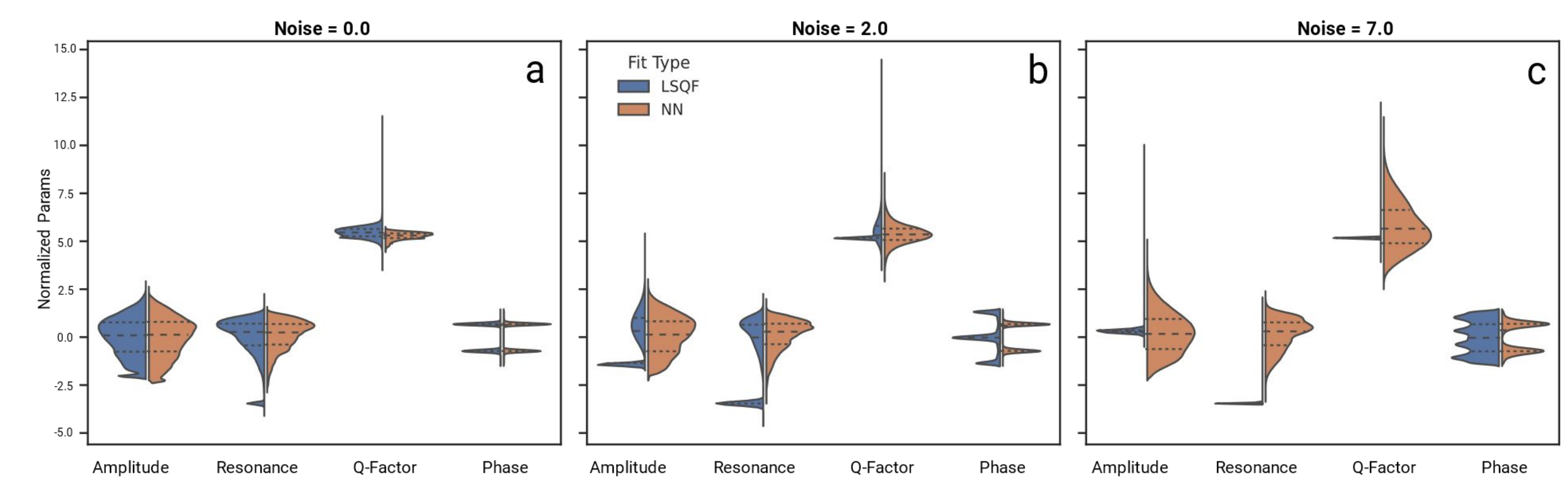
One method to accelerate machine learning inference is to bring computational resources as close to the data acquisition source as possible to minimize latencies associated with I/O and scheduling. Therefore, we leverage the National Instruments PXI platform to establish a direct, peer-to-peer channel over PCIe between an analog-to-digital converter and a Xilinx field programmable gate array (FPGA). Through the LabVIEW FPGA design suite, we develop this FPGA-based pipeline using cantilever resonances acquired in BE PFM to conduct real-time prediction of the simple harmonic oscillator (SHO) fit. To accomplish this, we use hls4ml to compile a high-level synthesis (HLS) representation of the neural network. Once this HLS model is synthesized to a register transfer level description (RTL), we implement the design on the FPGAs programmable logic. The parallelizable nature of FPGAs allows for heavily pipelined neural network implementations to achieve latencies on the order of microseconds. We currently benchmark our implementation at 36us per inference with a fourier transformation accounting for an additional 330us. At the expense of FPGA resources, we overlap data acquisition with computation to enable continuous acquisition and processing of response data. Overall, this work provides a foundation for deploying on-sensor neural networks using specialty hardware for real-time analysis and control of materials imaging systems.

Methods



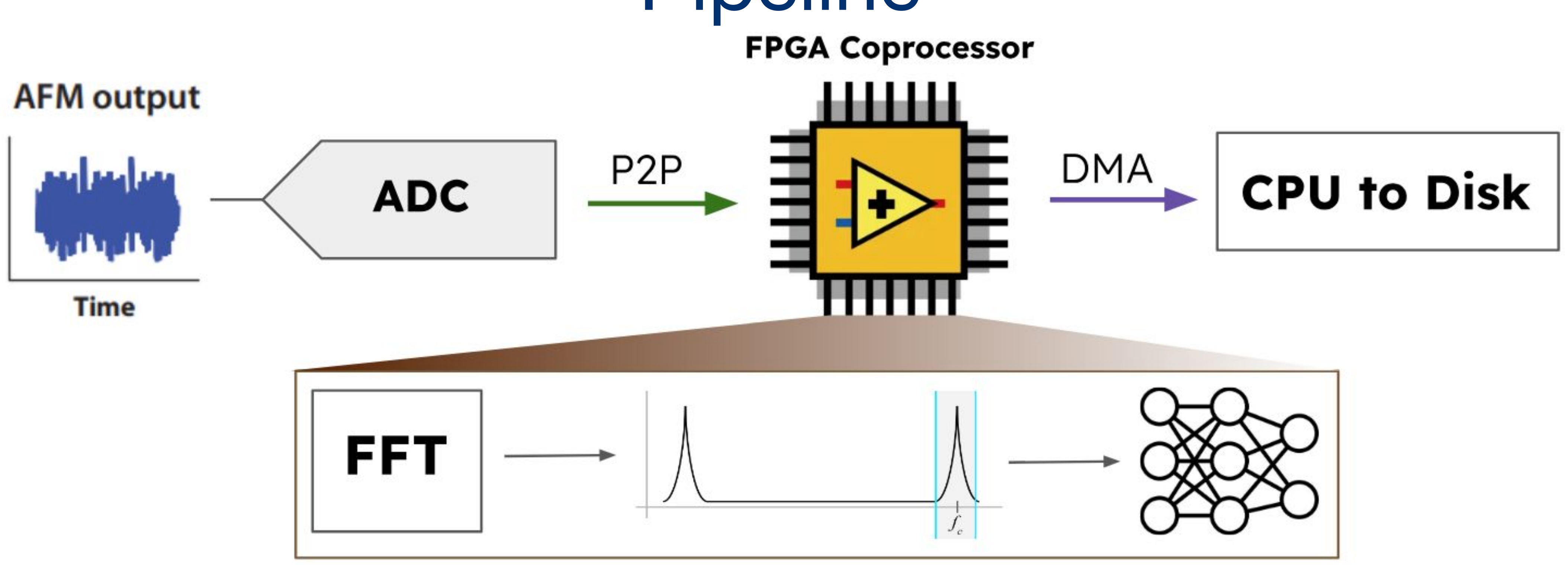
- Piezoresponse Force Microscopy (PFM): A set of imaging techniques where a sharp cantilever tip "scans" the surface of a sample; an AC voltage is applied to measure the piezoelectric properties of a material.
- Band Excitation PFM: A PFM technique where an excitation spanning a band of frequencies is applied, enabling study of the material's frequency dependence, dielectric and piezoelectric properties, and response to real world conditions (temperature, radiation, EM fields, mechanical stress, etc.)

Results



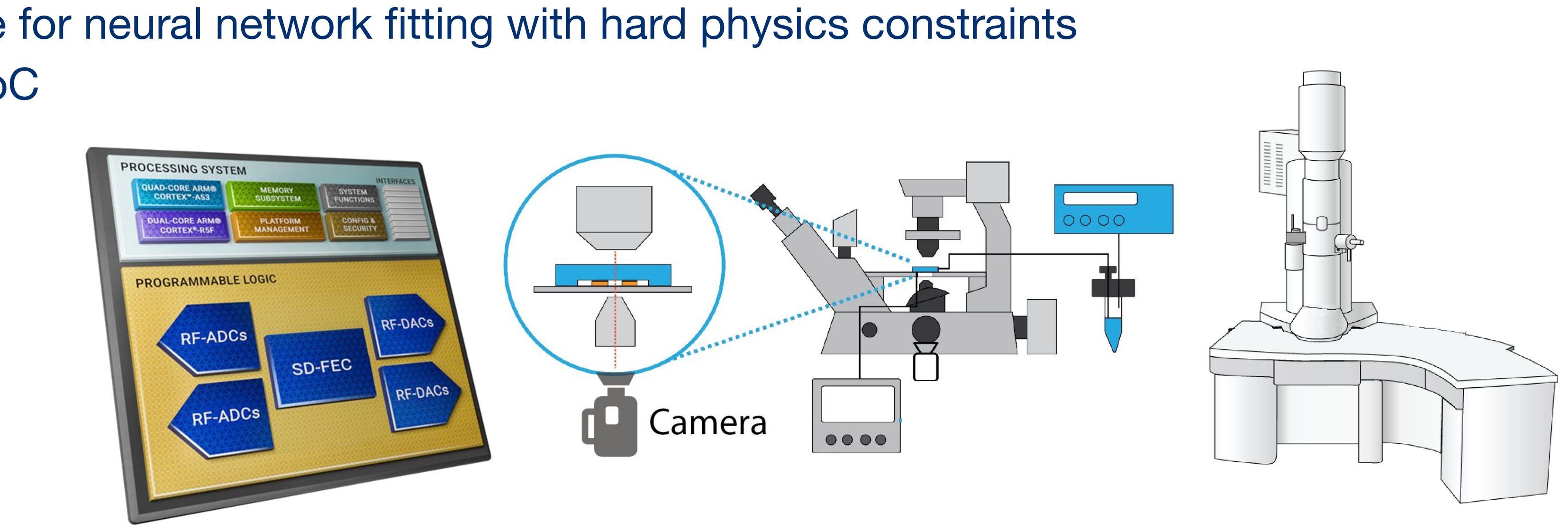
- SHO Fitter model and HLS model achieve ~0.053 MSE, outperforming least-squares fitting
  - Trained quantization aware; parameters quantized to 16 bits with marginal performance loss
- LabVIEW data acquisition and model firmware completed
- Achieved 36us first-in last-out FPGA model latency with over 60% of fabric resources still available

Pipeline



Future Work

- API for automated analysis
- Python package for neural network fitting with hard physics constraints
- Deploy on RFSoC



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