EMBEDDED SUBSYSTEM FOR SINGLE ATOM DETECTION

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Background and Introduction

QT3's atomic quantum processor relies on trapped arrays of laser-cooled Rubidium (Rb) atoms in a vacuum that are gated by optical pulses, and have their quantum state read out using fluorescence imaging. [1]

We want to create an FPGA algorithm for detecting the state of simulated trapped atom array and automated the readout process. [2]

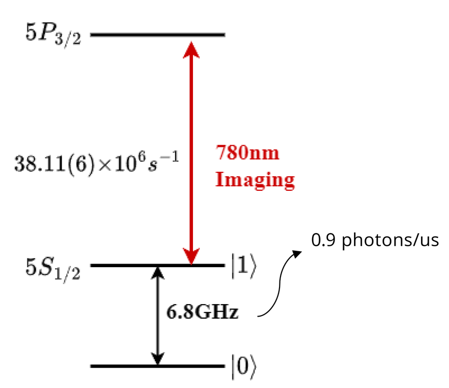

Fig.x. Rb level Diagram and imaging transition

Experimental Setup

- iXon Ultra 888 EMCCD
  - 1024 x 1024 resolution
  - 128 x 128 with 697 FPS
  - 13um x 13um pixel size
- Imaging lens
  - 1:1 magnification
  - 40mm Working Distance
- 1% Neutral Density filter
- OLED to simulate the Rb atoms
- EMCCD camera noise:
  - Readout noise
  - Photon "shot" noise
  - Thermal noise/dark current
  - Understanding camera noise aids image processing and test image simulation
- Python Interface Aids Camera and ARTIQ Configuration

```
variance (electrons) =   (readout noise)*(readout noise)  +
                         (number of thermal-electrons)    +
                         (number of photo-electrons)
```

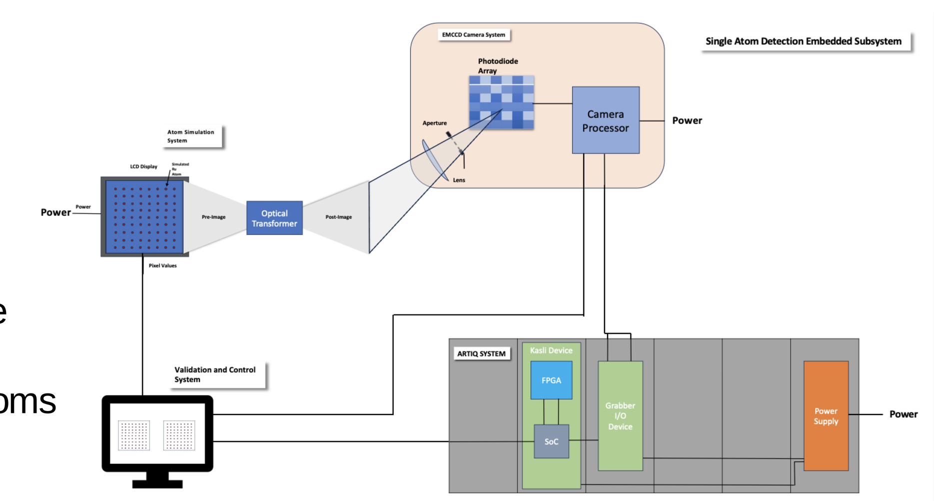

Fig.x. Block diagram for the imaging system

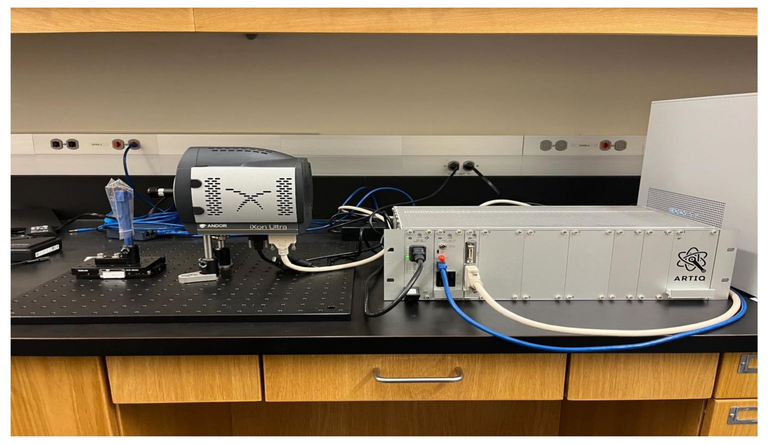

Fig.x. Optical seup

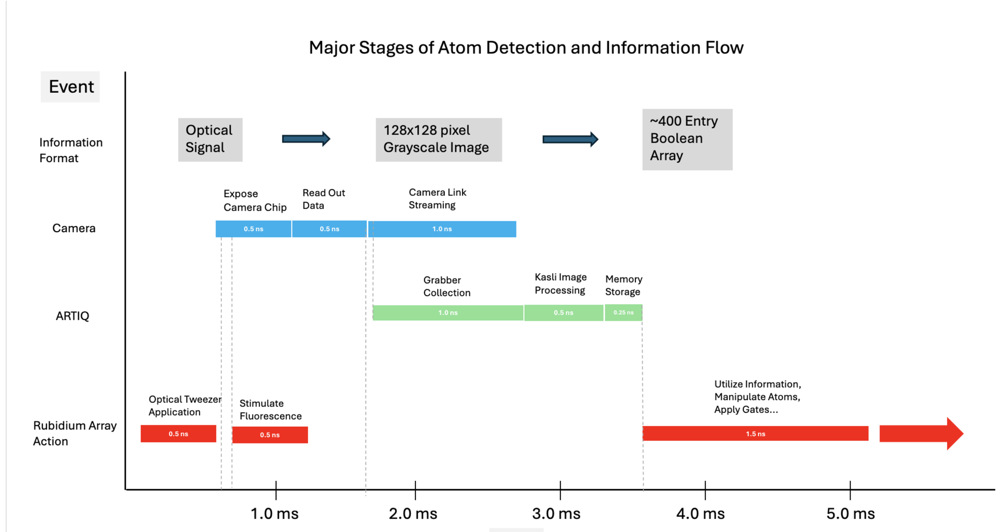

Fig.x. Major Stages of Atom Detection

Real Time Atom Detection

Project Objective: Develop gate-ware and software for control of an EMCCD camera and processing of images to determine the presence or absence of atoms at predetermined locations.

Performance goals: read out the occupation of an atom array in < 2 ms with fidelity of 99.9%

Technology used: ARTIQ based FPGA (Kasli), Andor EMCCD camera, Micro OLED Screen

The ARTIQ System

- The ARTIQ system: Modular open-source system for real-time experiment control
- Modules used: Kasli (FPGA-based board for system control), Grabber (receives image data)
- Grabber function: Receives 128 x 128 integer array data from high-frequency camera
- Purpose: Data used to detect atoms based on light intensity in specific regions
- Atom detection process:
  - ARTIQ sets up regions of interest (ROIs) using predicted atom locations
  - Pixel data filtered; if pixel corresponds to ROI, it's accumulated
  - Accumulated data compared to predetermined threshold
- Outcome: If accumulation surpasses threshold, atom presence assumed with high certainty

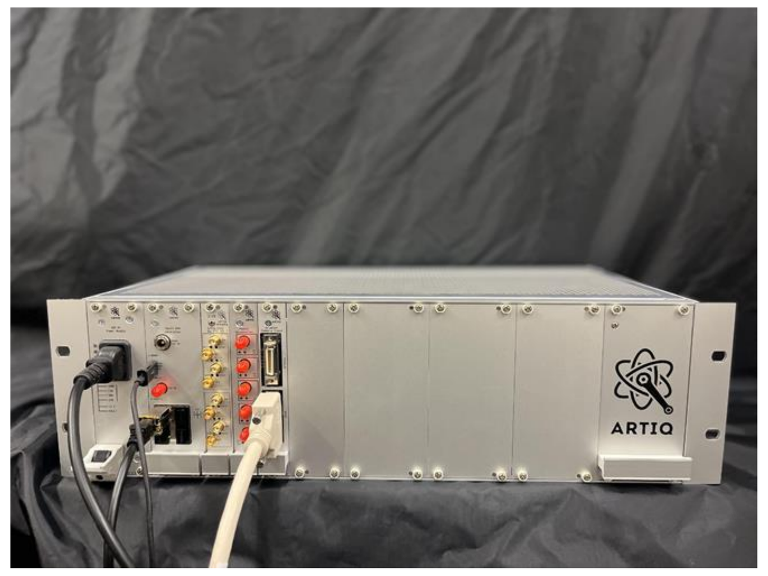

Fig.x. Schematic for Kasli.

Developing for Kasli

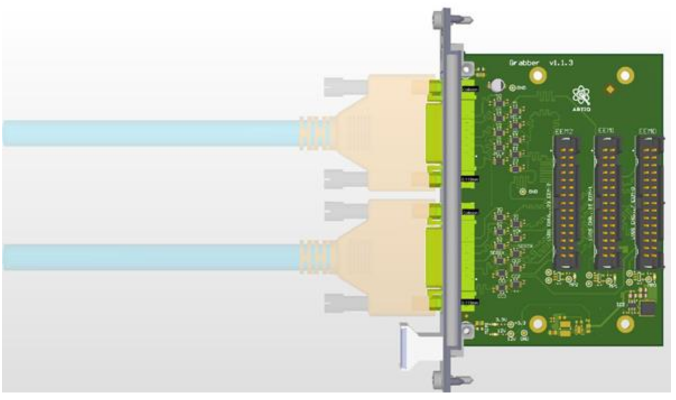

Fig.x. Schematic for Grabber.

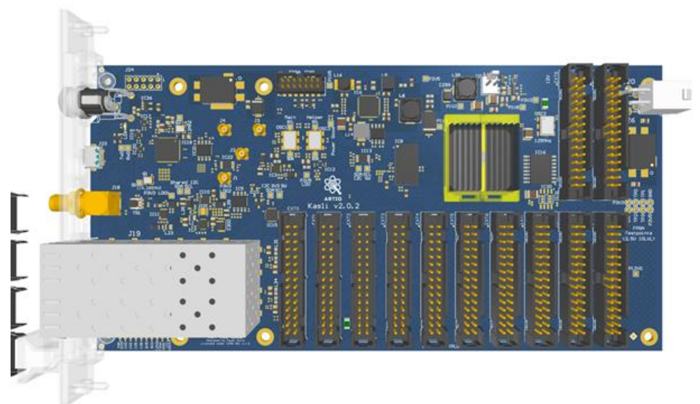

Fig.x. Schematic for Kasli.

- System requirement: Able to calculate sufficient ROIs for large tests
- Base Kasli support: Only 16 ROIs at a time
- Requirement for viability: Compute at least 200 ROIs simultaneously
- Solution: Changes to FPGA gateware on Kasli
- Implementation tool: Vivado on WSL system

Atom Detection Algorithm

Classification: Determine whether the atom is in the correct spin state. The distributions follow the Poisson distribution.

Definition and Ratio test: By comparing the likelihood for a given photon count in each distribution

$$f(k;\lambda) = \Pr(X{=}k) = \frac{\lambda^k e^{-\lambda}}{k!} \qquad Ratio = \frac{e^{-\lambda_1}\lambda_1^k/k!}{e^{-\lambda_2}\lambda_2^k/k!} = \frac{e^{-\lambda_1}\lambda_1^k}{e^{-\lambda_2}\lambda_2^k}$$

K-means: With the OpenCV package, find the threshold for a given photon count in each cluster. The threshold value is stored in the FPGA to determine the state in real-time.

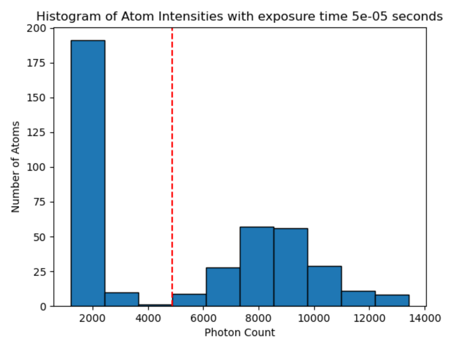

Fig.x. Photon count distribution for a given shot

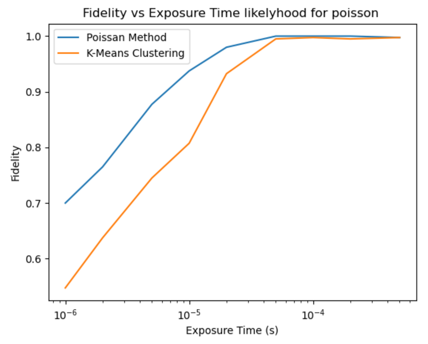

Fig.x. Exposure time versus the detection Fidelity

Simulated Atom Generation

- Using code developed by Winkelmann et. al., generated EMCCD atom images similar to experimental results [1]
- Image generation was modified for specific test data output and the project's EMCCD camera specifications
- Simulated images were used for parallel and efficient image processing development early on in the project lifecycle
- Longer image processing development time allowed for more comprehensive and detailed testing

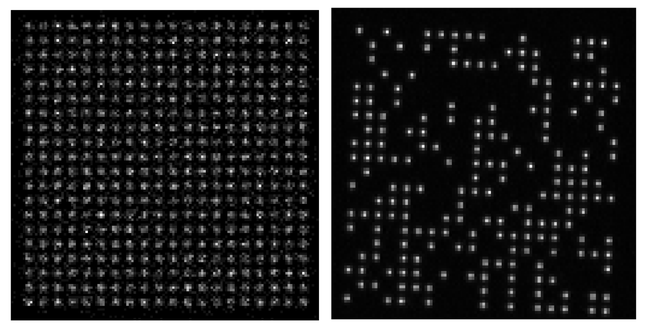

Fig X. Comparison of simulated image data (left) to real data captured by EMCCD camera (right)

Future Work, References, and Acknowledgments

The algorithm will be used in the Atomic Quantum Processor in the QT3 lab. It requires further development on the rearranging of the atom array to build the quantum processor based on the reconfigurable array.

[1] Saffman M 2016. Quantum computing with atomic qubits and Rydberg interactions: progress and challenges J. Phys. B: At. Mol. Opt. Phys. 49 202001
[2] Winklmann J, Tsevas D, Schulz M 2023. Realistic Neutral Atom Image Simulation arXiv preprint arXiv:2310.02836
[3] Kasprowicz G, Kulik P, Gaska M, Przywozki T, Pozniak K, Jarosinski J, Britton J W, Harty T, Balance C, Zhang W, Nadlinger D, Slichter D, Allcock D, Bourdeauducq S, Jördens R, and Pozniak K 2023 ARTIQ and Sinara: Open Software and Hardware Stacks for Quantum Physics arXiv preprint arXiv:2309.17233

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