Real-time Calibration of Quantum Gates

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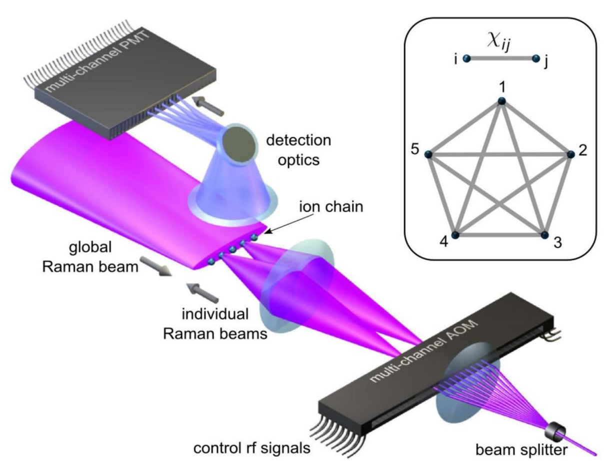
Trapped Ion System

- Alternating electric fields create 2D potential and confine ions into 1D chain.
- Hyperfine level of Ion as two-level quantum system (qubit)
- State rotation driven by Raman transition via optical beams.
- Entanglement of two qubit via coupling internal states of ions to ion chain motional modes



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Control Parameters

- Optical beams for quantum state manipulation (quantum gate) is controlled by acoustic-optic modulator (AOM), where several control parameters can affect the fidelity of the quantum gates:
  - steering location of control beams
  - Amplitude modulation (gain) of the beams
  - phase delay of the beams.
- These control parameters, can be carefully adjusted and optimized to compensate for the physical parameter drift in the trapped ion quantum computing system, maintaining high gate fidelity.

Native gate

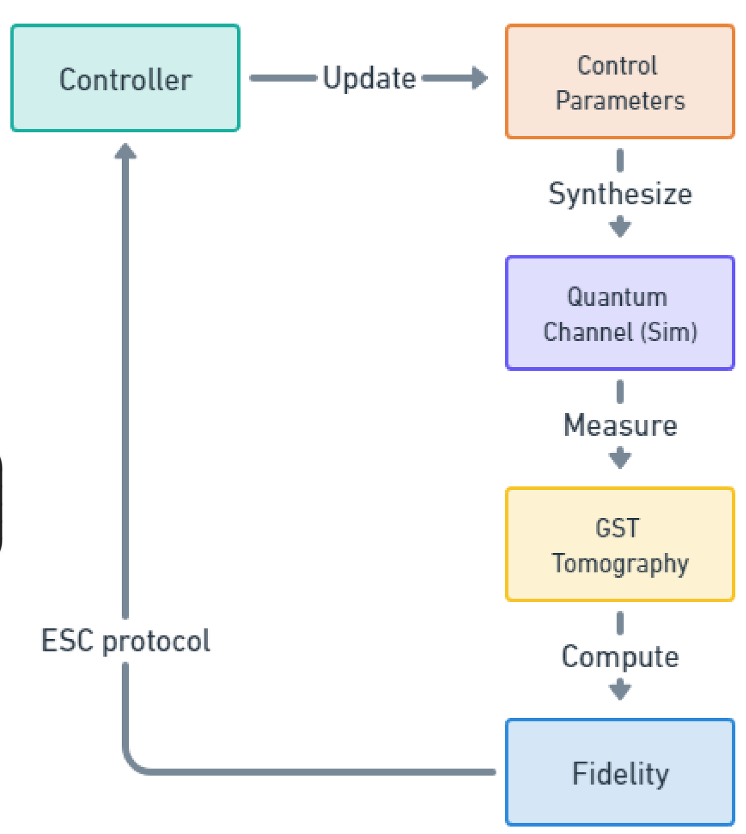
Single qubit

$$R(\theta,\phi)=\begin{pmatrix}\cos\frac{\theta}{2} & -ie^{-i\phi}\sin\frac{\theta}{2}\\ -ie^{i\phi}\sin\frac{\theta}{2} & \cos\frac{\theta}{2}\end{pmatrix}$$

two qubit

$$MS(\chi,\phi_1,\phi_2)=\begin{pmatrix}\cos\chi & 0 & 0 & -ie^{-i(\phi_1+\phi_2)}\sin\chi\\ 0 & \cos\chi & -ie^{-i(\phi_1-\phi_2)}\sin\chi & 0\\ 0 & -ie^{i(\phi_1-\phi_2)}\sin\chi & \cos\chi & 0\\ -ie^{i(\phi_1+\phi_2)}\sin\chi & 0 & 0 & \cos\chi\end{pmatrix}$$

Calibration Framework

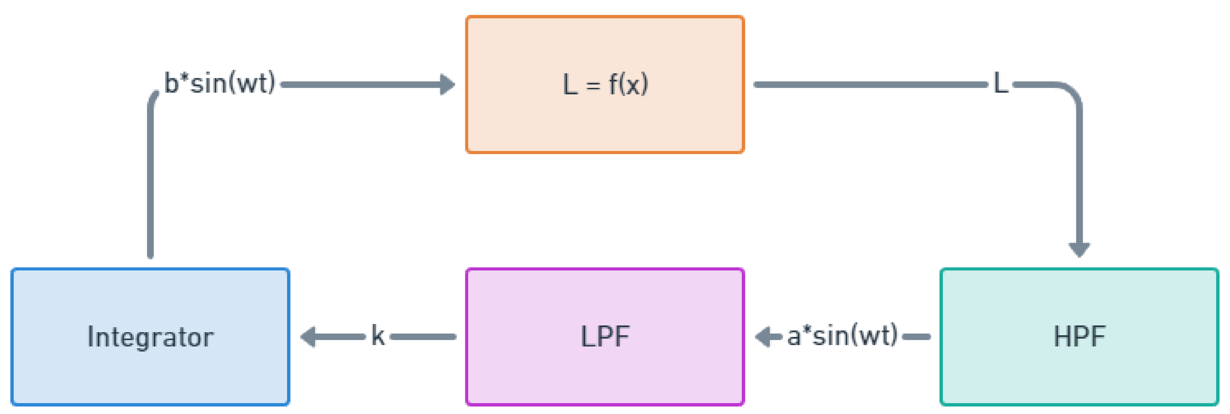


- Close-loop control
- Goal: a high gate fidelity

- GST: Gate Set Tomography
- ESC: Extremum Seeking Control

Extremum Seeking Control

- EST is a feedback control strategy used to optimize a system's performance by iteratively searching for the extremum of a cost or objective function.
- Constant parameter perturbations
- Maintain objective function L at high level.
- In our case, L is gate fidelity, x are control parameters.



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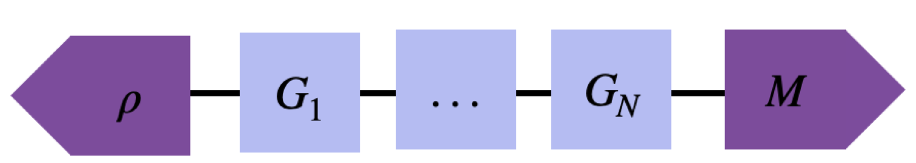
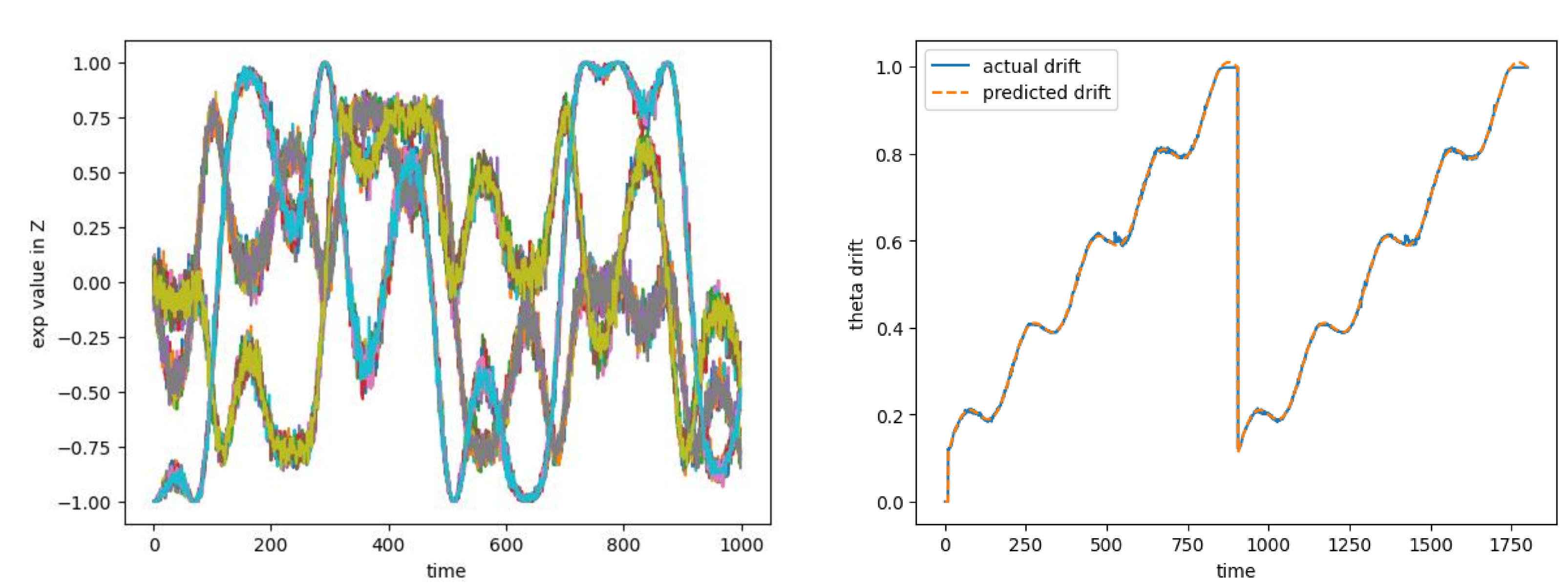
Objective Function

- **MS Gate Fidelity:**
- Fidelity measures how accurately a quantum gate performs.
- We define the objective function as the fidelity of the measured native gate from GST compared to the ideal native gate operation.

- **Gate Set Tomography (GST):**
- GST aims to determine the fidelity of the three elements of the quantum system: state preparation, quantum gates, and quantum measurement, based on experimental results.

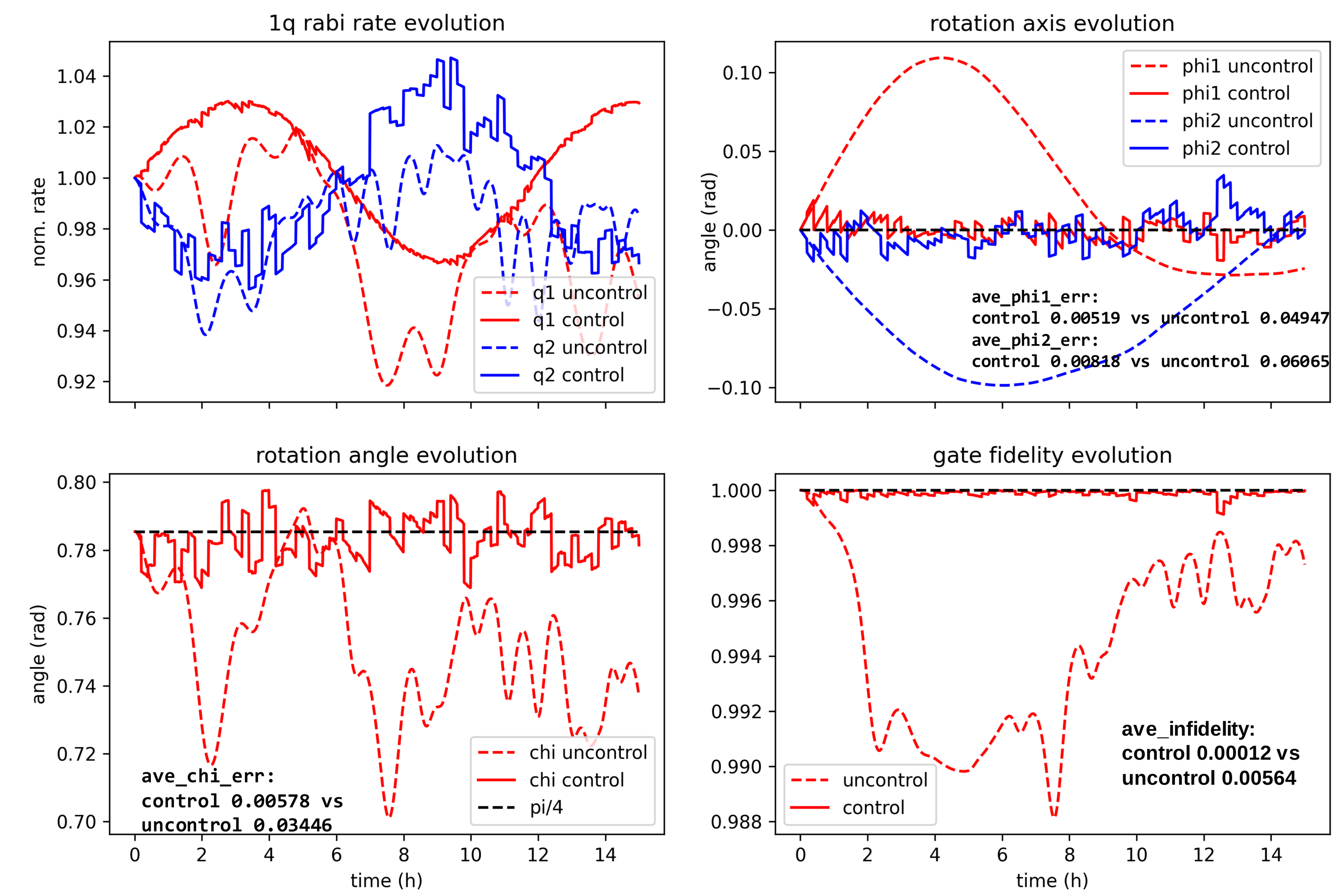


- **SHRED method:**
- Infer ground truth based on partial/probabilistic observations
- Reduce expensive cost incurred by full measurements
- Complement missing information from historical data trend
- Time-dependent data trajectory is learnt from historical data, by LSTM model



Simulation Result

- Simulated 2 qubit XX gate real-time calibration against physical parameters drift
- 2 Iteration, 66 total gate set tomography measurement per calibration
- 5 calibration per hour in the overall time scale of 15h
- Suppress rotation axis error by 10 times , rotation angle error by 7 times, gate infidelity by 40 times , compared to the uncontrol case
- Robust under measurement noise in rabi rates and rotation axes at the same level of the deviations caused by physical parameters drift



Future Work, References, and Acknowledgments

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