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Gate Set Tomography for Nitrogen-Vacancy systems

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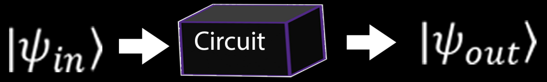
1. Motivation

- Quantum computing is a new and emerging field with many promising applications. i.e: Quantum machine learning, quantum cryptography, quantum chemichal engineering
- Before all these advancements can be made existing systems need to be able to scale. To do that these systems need low rates of noise and high rates of target gate fidelity.
- Gate Set Tomography (GST) is a protocol for characterising quantum systems. Nitrogen-Vacancacy systems are a way to physically implement a quantum information system. Applying GST to NV systems could help in finding sources of noise, and consequently to design quantum processors with reduced noise.

Gate Set Tomography

Quantum circuits can be regarded as a black box.



GST is a protocol for detailed, predictive characterisation of logic operations on quantum computing processors [1].

Python GST implementation (pyGSTi) is an open-source framework implementing GST.

Sets of gates to prepare and measure (fiducials) and to probe error space (germs) are found. These are then used to construct an experiment design, as seen in figure 1.

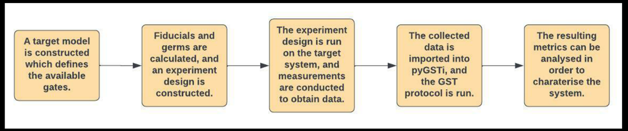


Figure 1: Flowchart of pyGSTi workflow

Nitrogen-Vacancy System

One possible way to implement a quantum bit (qubit) is by using an electron spin inside a Nitrogen-Vacancy (NV) centre in a diamond lattice [2], as seen in figure 2.

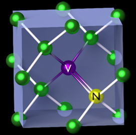


Figure 2:
A Nitrogen-Vacancy centre system.

These qubits are realised by replacing a carbon atom in these lattices by a nitrogen atom.
This creates a vacancy in which an electron can then be manipulated using microwave (MW) pulses enabling quantum computing.

The electron can couple to the nitrogen nucleus, if not accounted for in control calibration this coupeling can produce a signifcant amount of noise. Therefore it is especially interesting to apply GST to NV systems, which seeks to characterise systems.

Research Question

How can pyGSTi be employed to characterise operations in an NV based quantum device when comparing simulated data with experimental data?

Subquestions

- What does pyGSTi tell us when we compare experimental models with simulated models with differing nitrogen initialisation states?
- What does pyGSTi tell us when we analyse models which employ an XY4 echo?
- How can GST results be visualised in a way that is intuitive and simple to understand?

2. Methodology

Problem Statement

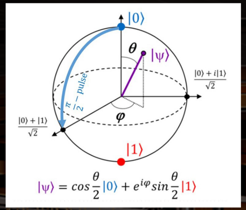


Figure 3: Bloch sphere example.

Quantum states are linear combinations of multiple states (superposition). These can be visualised on the Bloch Sphere, as seen in figure 3.

Gates can then be applied to change the quantum state, e.g: X gate, which rotates the quantum state with π radians around x-axis.

Physical implementation of gates are not perfect, due to e.g: background noise, laser spillover, thermal bombardment.

GST aims to charaterise system to understand where noise is coming from.

An echo can be employed to minimise decoherence.
This can be seen as “kicking” the system to avoid it from “relaxing”.
XY4 echo pulse sequence seen in figure 4

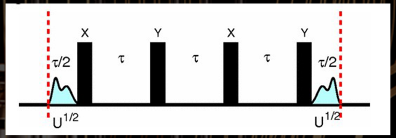


Figure 4: The XY4 echo pulse sequence

Model Construction

- Two models were constructed, a 3 gate model and a 5 gate model Tables 1 and 2 shows the germs and fiducials gate sets of these models.
- Experimental data was generated by an NV system of the Taminiau group at QuTech.
- Simulated data was generated by a numerical solver written in QuTiP.
- Experimental data sets vary in nitrogen initialisation states. These states are the m1, p1, 0 and mixed state,
- Simulated datasets vary in nitrogen initialisation fidelity.
- The 3 gate models also utilised the XY4 echo, in order to minimise decoherence.
- All data sets were run by pyGSTi. The GST results were then used to generate metrics. These metrics were then analysed to characterise the system.

3 gate model	
fiducials	germs
	I
$X^{\frac{1}{2}}$	$X^{\frac{1}{2}}$
$Y^{\frac{1}{2}}$	$Y^{\frac{1}{2}}$
$(X^{\frac{1}{2}}\ X^{\frac{1}{2}})$	$(X^{\frac{1}{2}}\ X^{\frac{1}{2}})$
$(X^{\frac{1}{2}}\ X^{\frac{1}{2}}\ X^{\frac{1}{2}})$	$(I\ I\ I\ I\ I\ Y^{\frac{1}{2}})$
$(Y^{\frac{1}{2}}\ Y^{\frac{1}{2}}\ Y^{\frac{1}{2}})$	$(I\ I\ I\ I\ X^{\frac{1}{2}}\ Y^{\frac{1}{2}})$
	$(I\ I\ I\ I\ Y^{\frac{1}{2}}\ X^{\frac{1}{2}})$
	$(I\ I\ Y^{\frac{1}{2}}\ X^{\frac{1}{2}}\ X^{\frac{1}{2}}\ X^{\frac{1}{2}})$
	$(X^{\frac{1}{2}}\ X^{\frac{1}{2}}\ Y^{\frac{1}{2}}\ Y^{\frac{1}{2}}\ X^{\frac{1}{2}}\ Y^{\frac{1}{2}})$
	$(I\ I\ X^{\frac{1}{2}}\ X^{\frac{1}{2}}\ X^{\frac{1}{2}}\ Y^{\frac{1}{2}})$

Table 1: germs and fiducials of 3 gate model

5 gate model	
fiducials	germs
I	I
$X^{\frac{1}{2}}$	$X^{\frac{1}{2}}$
$Y^{\frac{1}{2}}$	$Y^{\frac{1}{2}}$
$(X^{\frac{1}{2}}\ X^{\frac{1}{2}})$	X
$(X^{\frac{1}{2}}\ X^{\frac{1}{2}}\ X^{\frac{1}{2}})$	Y
$(Y^{\frac{1}{2}}\ Y^{\frac{1}{2}}\ Y^{\frac{1}{2}})$	

Table 2: germs and fiducials of 5 gate model

4. Future Work

1) Further development of GSTBlochWidget.
For example, the number and complexity of metrics used could be further expanded upon.

2) Charaterise XY4 echo pulses using pyGSti.
In our models these pulses were implicit, but the echo pulses should also be characterised.

3) Investigate calibration control, to find factor 2 disrepency.
Gathering more data sets from the m1 and p1 states with differing calibration parameters could offer valuable insights.

4) Investigate optimal germ and fiducial selection.
For the 5 gate models single gate germs were used.
This is a sub-optimal solution.

5) Perform GST on 2 qubit system and calculate Markovianity by deconstructing results.
This could offer insights as to the nature of the noise that occurs due to coupling

7) Build pyGSTi pipeline to calculate multiple GST runs in parallel.
This could save valuable research time.

3. Results and Discussion

Utilised Metrics

Three metrics with difering objectives were used for this research:

1) **The Nσ metric** quantifies the “goodness of fit”.
It tells us how well the estimated gates fit the data.

2) **The error generator** metric quantifies the types of errors observed.
It tells us the proportions of Hamiltonian, stochastic and active errors.

3) **The diamond norm** metric measures the “single use distinguishability”.
It tells us the probability that two gates can be distinguished, ie: how “close” they are.

GSTBlochWidget

- Interpreting GST results can be challenging, therefore an interactive widget was developed.
- GSTBlochWidget loads estimated gates from GST results, and visualises these. Gates can be applied via buttons, and resulting quantum state and fidelity are shown. Composed circuits can be saved in text format for later analysis.
- For example the Y^(1/2) gate of model with initialisation state 0. We knew from the metrics that this gate has bad perfomance. GSTBlochWidget enables us to see bad perfomance in action.

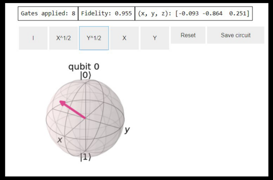

Gates applied: 8 | Fidelity: 0.955 | (x, y, z): [-0.093 -0.864 0.251]

Figure 4: Example of GSTBlochWidget with multiple gates applied.

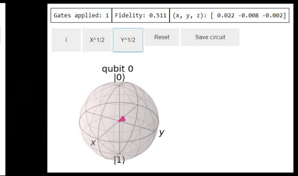

Gates applied: 1 | Fidelity: 0.511 | (x, y, z): [0.022 -0.008 -0.002]

Figure 5: Example of GSTBlochWidget with one bad gate applied.

Effects of Nitrogen Initialisation and XY4 echo

- Proportion of stochastic errors go down when the target model is simulated. This is especially the case for models where init_state=mixed. This is a good sign, as our simulation seems to capture noise sources.
- The X^(1/2) and Y^(1/2) gates of the m1 and p1 experimental 3 gate models have diamond norms which differ by a factor 2. This might be due to a calibration fault with respect to the energy levels of the corresponding nitrogen states.
- Nσ of model with mixed state without XY4 echo is two orders of magnitude larger than with echo. This means that the XY4 echo effectively suppresses noise due to coupling.

Compared model: 3_gate_exp_init_state=m1				
Gate	$\mathbb{H}$	$\mathbb{S}$	$\mathbb{A} + \mathbb{C}$	D norm
Target model: ideal_model				
I	96.4%	2.9%	0.6%	0.006327
$X^{\frac{1}{2}}$	99.9 %	0.1%	0%	0.034369
$Y^{\frac{1}{2}}$	99.9 %	0.1 %	0%	0.050599
Target model: 3_gate_sim_init_fid=0.95				
I	98.5%	1.2%	0.3%	0.009337
$X^{\frac{1}{2}}$	99.9 %	0.1%	0%	0.033937
$Y^{\frac{1}{2}}$	99.9 %	0.1 %	0%	0.048303

Table 3: Error generator and diamond norm of 3 gate model with init_state=m1

Compared model: 3_gate_exp_init_state=mixed				
Gate	$\mathbb{H}$	$\mathbb{S}$	$\mathbb{A} + \mathbb{C}$	D norm
Target model: ideal_model				
I	93.7%	4.4%	1.8%	0.002326
$X^{\frac{1}{2}}$	9.3 %	76.4%	14.3%	0.00205
$Y^{\frac{1}{2}}$	61.8 %	34.3 %	3.9%	0.00287
Target model: 3_gate_sim_init_fid=0				
I	99.2%	0.5%	0.3%	0.00551
$X^{\frac{1}{2}}$	81.7 %	15%	3.3%	0.003864
$Y^{\frac{1}{2}}$	60.3 %	35.1 %	4.6%	0.002951

Table 4: Error generator and diamond norm of 3 gate model with init_state=mixed

References: [1] Nielsen et al, Gate Set Tomography, 2021. [2] Aboubeih et al, rom atomic-scale imaging to quantum fault-tolerance with spins in diamond, 2021. [3] Li et al, Concepts of quantum non-Markovianity: a hierarchy, 2018