Towards Optimal Constructions of Dynamically Corrected Quantum Gates

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Dynamical Quantum Error Correction = Non-dissipative QEC:
Open-loop Hamiltonian engineering based on [a fixed set of] unitary control operations.

Simplest setting: Multipulse decoherence control for quantum memory ⇒ DD

Key principle: Time-scale separation ⇒ Coherent averaging of interactions
Paradigmatic example: Spin echo ←── Effective time-reversal
Hahn 1950.

Theory: Average Hamiltonian formalism
Haeberlen & Waugh 1968; Waugh 1982...

Key feature: Open quantum system dynamics
✓ Error component includes coupling to a quantum environment/bath...
✓ Nature of environment need not be specified, except qualitatively...
\[
\frac{\tau_{control}}{\tau_c} \quad \text{Small parameter}
\]

→ Perturbative error cancellation enforced
Goal: Better address timing and sequencing constraints...

Even when BB assumption is accurate, min control time scale/pulse repetition rates are finite...

Q1: What is the best possible DD performance for specified timing resources?
   - Bandwidth-Adapted DD (BADD)  

Q2: Can such performance be achieved for arbitrarily long storage time and how?
   - Bandwidth-Adapted Long-time DD (BALDD)  
   Khodjasteh, Biercuk & LV, forthcoming.

Scalable lab implementations will face sequencing limitations from digital electronics...

Q3: How can we ensure hardware compatibility and minimize DD sequencing complexity?
   - Walsh DD (WDD)  
Goal: Better address system and control limitations/non-idealities...

Even with otherwise perfect control, realistic control amplitudes are finite...

→ Open-loop Hamiltonian engineering with bounded control inputs substantially harder:

\[ H_{\text{err}} \approx 0 \text{ during each BB pulse, whereas EPG} = O(\tau \|H_{\text{err}}\|) \text{ for 'fat' pulses...} \]

Q1: How [and how well] can we decouple with realistic pulses?

← Eulerian DD (EDD), RUDD...  
LV & Knill 2003; Pasini et al 2008; Uhrig & Pasini 2009...

Q2: Can we suppress decoherence while effecting a non-trivial quantum gate?

← Strongly modulating pulses, Dynamically Corrected Gates (DCGs)...  
Fortunato et al 2002; Pryadko & Quiroz 2008...  
Khadjasteh & LV 2009...

Q3: To what extent can DQEC compensate for decoherence and control errors together?

Outline:

I. DCGs, first-order and beyond – What they are and how to make them...
II. How to enhance DCG efficiency and flexibility – Toward combining 'DCG + OCT'...
I. Analytical
DCG Framework

Khodjasteh & LV, PRL 102, 080501 (2009); PRA 80, 032314 (2009);
Khodjasteh, Lidar & LV, PRL 104, 090501 (2010); [Longer paper coming soon...]
Target system $S$ couples to quantum bath $B$ via interaction Hamiltonian $H_{SB}$:

$$H = \left[ H_{S,g} + H_{S,err} \right] \otimes I_B + I_B \otimes H_B + H_{SB} \equiv \sum_a S_a \otimes B_a$$

→ System operators $\{S_a\}$ form Hermitian basis, with $S_0 = I_S$ and $S_a \neq 0$ traceless.

→ Bath operators $\{B_a\}$ are bounded but otherwise arbitrary [possibly unknown].

Environment $B$ is uncontrollable: Controller acts on system only,

$$H_{\text{tot}}(t) \equiv H + H_{\text{ctrl}}(t), \quad H_{\text{ctrl}}(t) = \sum_m \left( H_m \otimes I_B \right) h_m(t)$$

$$U_{\text{ctrl}}(t) = T\exp \left\{ -i \int_0^t ds \, H_{\text{ctrl}}(s) \right\}$$

→ Universal control on $S$ may or may not require a non-zero [drift] system Hamiltonian.

→ Semi-classical limit: Random modification of system Hamiltonian, $H_S \rightarrow H_S(t)$. 
**Error model assumptions**

- **Error model** includes any deviation between actual controlled evolution and intended one:
  
  - Ideal gate propagator over duration $T$:
    
    $$U^0(T) = Q \otimes I_B = Texp \{-i \int_0^T ds \left[ H_{ctrl}(s) + H_{S,g} \right] \otimes I_B \}$$

  
  - Actual gate propagator over duration $T$:
    
    $$U(T) = Texp \{-i \int_0^T ds \left[ H_{ctrl}(s) + H_{S,g} + H_{err} \right] \} \equiv Q \exp(-i E_Q)$$

  
  **Simplifying assumptions:**

  1. **Perfect control** – No errors are introduced by the controller;
  2. **Driftless system** – Can effectively assume that $H_{S,g} = 0$, $H_S \equiv H_{S,\text{err}} \Rightarrow$

    $$U_{ctrl}(T) \equiv Q = Texp \{-i \int_0^T ds H_{ctrl}(s)\}, \quad U(T) = Q Texp \{-i \int_0^T ds U^*_{ctrl}(s) H_{err} U_{ctrl}(s)\}$$

- **Focus on arbitrary linear [non-Markovian] decoherence on qubits:**

  $$H_{SB} = \sum_{i=1}^n \sum_{a=x,y,z} \sigma_a ^{(i)} \otimes B_a ^{(i)}, \quad H_{err} = I_S \otimes H_B + H_{SB}$$

  - Error operators we wish to suppress:

    $$\Omega_{err} = \text{Span}\{ \sigma_\alpha ^{(i)} \otimes B_\alpha ^{(i)} \ | \ B_\alpha ^{(i)} \text{ nonzero in } H_{err} \}$$
Control assumptions

Error action operator leads to a natural measure to quantify EPG:

\[
\text{EPG} = \| \text{mod}_B \left( E_Q \right) \|_{op} \Rightarrow \| \rho_S(\tau) - \rho_S^0(\tau) \|_1 \leq \| \text{mod}_B \left( E_{Q[\tau]} \right) \|_{op}
\]

Non-pure-bath component \hspace{1cm} Actual \hspace{1cm} Ideal

Control resources: Universal set of tunable 'primitive' Hamiltonians

e.g. \[
\{ h_x(t)\sigma_x^{(i)}, h_y(t)\sigma_y^{(i)}, h_{zz}(t)\sigma_z^{(i)}\otimes\sigma_z^{(j)} \}, \quad i, j = 1, \ldots, n
\]

Assumptions:

(C1) Finite-power and bandwidth constraint:

Bounded control amplitude, \( h_a(t) \leq h_{\text{max}} \) and minimum gate duration, \( \tau_{\text{min}} > 0 \);

(C2) Stretchable and scalable pulse profiles:

⇒ Same primitive gate \( Q \) can be implemented with different pulse shapes and speed
DCG block structure:

→ Cascade $N$ primitive gates.

→ If each individual EPG is sufficiently small,

$$E_{(Q_1[\tau_1] \ldots Q_N[\tau_N])} = E_{Q_1[\tau_1]} + P_1^\dagger E_{Q_2[\tau_2]} P_1 + \ldots + P_{N-1}^\dagger E_{Q_N[\tau_N]} P_{N-1} + C^{[2^+]},$$

$$P_{N-1} = Q_{N-1} \ldots Q_1$$

as long as the [discrete-time] Magnus expansion converges, $\sum_i \| \text{mod}_B (E_{Q_i[\tau_i]}) \| < \pi$.

• EPGs do not simply add: Individual errors are 'modulated' by the applied control path.
  Because control path is known, errors have a systematic dependence upon gate duration...

• Seek a control modulation s.t. the effect of $H_{err}$ is perturbatively [coherently] averaged out:

$$\text{EPG}_{\text{uncorrected}} = \| \text{mod}_B (E_{Q^{\text{unc}[\tau_i]}}) \| \propto \tau + O(\tau^2)$$

$$\text{EPG}_{\text{corrected}} = \| \text{mod}_B (E_{Q^{\text{corr}[\tau_i]}}) \| \propto \tau^2 + O(\tau^3)$$
If target gate $Q = I$, a solution is provided by EDD:

- Primitive gates implement the generators $\{\gamma_i\} \in \Gamma$, $i=1,...,G$.
- Generators are applied by following an Eulerian cycle on the Cayley graph of $G_{DD}$.

$$E_{EDD} = \sum_{l=1}^{L} \sum_{i=1}^{G} U^\dagger_{g_i} E_{\gamma_i} U_{g_i} + E_{EDD}^{2+1}, \quad \| \text{mod}_B(E_{EDD}) \| = \| \text{mod}_B(E_{EDD}^{2+1}) \| = O(\tau^2)$$

Linear decoherence on qubits:

$G = \mathbb{Z}_2 \times \mathbb{Z}_2 \rightarrow \{I^{(\text{all})}, X^{(\text{all})}, Y^{(\text{all})}, Z^{(\text{all})}\}, \Gamma \equiv \{X, Y\}$

- Collective generators can be implemented by collective primitive Hamiltonians:

$$X^{(\text{all})} = X_1 \otimes \cdots \otimes X_n = \exp \left[ -i \int_0^\tau h_x(s) (\sigma_x^{(1)} + \cdots + \sigma_x^{(n)}) \, ds \right]$$

- In EDD, no information about how primitive EPGs depend on control implementation is used/required!

- No-Go thm for 'black-box' DQEC: Only gates that commute with $\Omega_{err}$ can be achieved with 'control-oblivious' design...

Euler cycle: $X \ Y \ X \ Y \ X \ Y \ X$

Cycle length: $\tau_{EDD} = (L \times G) \tau$
DCGs beyond NOOP

Simple way to evade No-Go: Identify two combinations of primitive gates that share same first-order error ⇒ [First-order] 'balance pair' for target gate $Q$:

$$Q_* = Q \exp(-iE_Q), \ I_Q = \exp(-iE_Q)$$

Modified Eulerian construction: Implement control path which begins at $I$ and ends at $Q$ on 'augmented' graph ⇒

(i) To non-identity vertex, attach edge labeled by $I_Q$
(ii) To identity vertex, attach edge labeled by $Q_*$

$$E_{DCG} = E_{EDD} + \sum_{i=1}^{G} U_g^\dagger E_\gamma U_g + E_{DCG}^{[2]}$$

Total 1st-order error vanishes as long as the primitive errors $E_\gamma$ and $E_Q$ obey DD condition ⇒

$$\| \text{mod}_B(E_{DCG}) \| = \| \text{mod}_B(E_{DCG}^{[2]}) \| = O(\tau^2)$$

Significantly smaller error wrto 'direct switching'.
Finding gates with same error: Balance pairs

Key insight: Map out and exploit relationship between primitive error and control profile...

Naive balance pairs: Assume access to a stretchable and (sign-)reversible gating profile,

\[ Q[	au] = \text{Exp}\left\{-i \int_0^\tau h_Q(t)H_Q dt\right\} \]

\[ Q[s \tau] = \text{Exp}\left\{-i \int_0^{s \tau} h_Q\left(\frac{t}{s}\right)H_Q dt\right\} \]

\[ E_Q[\tau] \quad \rightarrow \quad E'_Q[s \tau] = s E_Q[\tau] \]

→ Example of primitive gate combinations sharing the same [leading] error:

\[ I_Q \equiv Q'[\tau]Q[\tau], \quad Q_* \equiv Q[2 \tau], \quad \text{mod}_B(E_{I_Q}) = \text{mod}_B(E_{Q_*}) + O(\tau^2) \]

Enhanced balance pairs: Assume access to [just] stretchable gating profiles,

→ Portable primitive gate combinations sharing the same [leading] error:

\[ I_Q \equiv I_Q^{[0]} = Q^{-1}[\tau]Q[2 \tau], \quad Q_* \equiv Q_*^{[0]} = Q[\tau]Q^{-1}[\tau]Q[\tau], \quad \text{mod}_B(E_{I_Q}) = \text{mod}_B(E_{Q_*}) + O(\tau^2) \]

→ DCG resource overheads:

\[ 8(2) + 3 \times 4(2) \Rightarrow 20(8) \text{ primitives per DCG for linear decoherence (pure dephasing)} \]
Strategy: Increase order of cancellation by using recursive design ⇒ Concatenated DCGs

\[ \{ Q^{[0]} \} \equiv \text{Primitive gates}; \quad \{ Q^{[1]} \} \equiv 1\text{st-order DCGs}; \quad \ldots \quad \{ Q^{[m]} \} \equiv m\text{th-order DCGs} \]

- Balance pairs of order \( m \) may be given in terms of \( m \)th-order implementation of \( Q \) and \( Q^{-1} \):

\[
I_Q^{[m]} = Q^{[1][m]}[\tau] Q^{[m]}[2^{1/(m+1)}\tau], \quad Q_*^{[m]} = Q^{[m]}[\tau] Q^{-1[1][m]}[\tau] Q^{[m]}[\tau], \quad m \geq 0
\]

\[
\text{mod}_B(E_{I_Q}) = \text{mod}_B(E_{Q_*}) + O(\tau^{m+2})
\]

- CDCG algorithm ⇒ Embed lower-order DCGs as components for EDDs and balance pairs:

1. Set \( m = 0 \).

2. Start with strechable \( m \)th-order primitive gates \( Q = Q^{[m]} \) and their error model \( \Omega_{\text{err}}^{[m]} \).
   - \( \Omega_{\text{err}}^{[m]} \) includes all errors uncorrected at level \( m \) ⇒ Identify smallest group \( G^{[m]} \), of size \( G_m \), that decouples all errors in \( \Omega_{\text{err}}^{[m]} \).
   - Represent the \( L_m \) generators of \( G^{[m]} \) as primitive gates or combinations thereof.

3. Use generators for \( G^{[m]} \) and the construction for \( m \)th-order balance pair to generate \( Q^{[m+1]} \).

4. Repeat recursively by substituting the newly constructed gates for the old ones:
   \[ m = m + 1 \]. Go to step 2.
CDCGs: Performance analysis

Key step in establishing error bound ⇒ show that the Magnus expansion of error $E_Q^{[m]}$ contains only terms that start at $O(\tau^{m+1})$ (modulo pure-bath terms)...

→ Starting at $m = 0$ with primitive gates of duration $\tau$, duration at order $m$ obeys

$$
\tau_{m+1} = \left[ G_m L_m + 3 + (G_m - 1)(1 + 2^{1/(m+1)}) \right] \tau \quad \Rightarrow \quad \tau_{m+1} \leq [G_m (L_m + 3)]^m \tau \equiv (\chi_m)^m \tau
$$

Euler path Balace pairs

→ [Worst-case] error upper bound, $c = O(1)$:

$$
\| \text{mod}_B(E_{DCG}^{[m]}) \| < c 4^m (\chi_m)^{m^2 + m} (\| H_{err} \| \tau)^{m+1}
$$

For fixed minimum switching time $\tau$, error bound implies optimal concatenation level,

$$
m_{opt} = \left\lfloor -\frac{1}{2} \log_\chi \left( 4 \tau \| H_{err} \| + 1 \right) \right\rfloor, \quad \chi \equiv \chi_{opt}
$$

below which CDCGs are guaranteed to perform better than first-order DCGs.

→ Smaller $\tau$ ⇒ Finer temporal resolution of CDCG 'digitized pulse profile'...
Case study: Electron spin qubit undergoing hyperfine decoherence in QD

\[ H_{\text{error}} = I_S \otimes \sum_{k=1}^{N} D_k \mathbf{I}_k \cdot \mathbf{I}_k + \hat{\sigma} \otimes \sum_{k=1}^{N} A_k \mathbf{I}_k, \quad N = 5 \]

\[ \Omega_{\text{err}}^{[m]} = \Omega_{\text{err}} = \text{Span}\{ \sigma_a \otimes B_a, a = x, y, z \}, \text{ independent upon } m \]

\[ G^{[m]} = G = \mathbb{Z}_2 \times \mathbb{Z}_2 \rightarrow \{ I, X, Y, Z \}, \Gamma = \{ X, Y \} \Rightarrow \chi_m = \chi = 4 \times 5 = 20 \]

Gate sequence [right to left!] for mth-order DCG:

\[ Q^{[m+1]} = Q^{[m]} X^{[m]} Y^{[m]} X^{[m]} Y^{[m]} I_Q X^{[m]} I_Q Y^{[m]} I_Q X^{[m]} \]

Target gate: \[ Q = \exp(-i \frac{2 \pi}{3} \sigma_x) \]

Steeper error-corrected 'slopes' achieved as concatenation level grows, if switching time is small.

Fidelity improvement by as many as 13 orders of magnitude...
Recently implemented Mølmer-Sørensen 'composite' gate sequences can be interpreted as CDCGs under a simple error model...

\[
U_Q(t) = \exp\left[ S_N(\alpha(t)a^\dagger - \alpha(t)^* a) \right] Q, \quad Q = \exp[-i\Phi(t)S_N^2] \\
\alpha(t) = \frac{\Omega}{2} \int_0^t \exp[-i(\delta + \Delta)s]ds \quad \Delta = \text{Detuning error} \ll \delta
\]

Gate relies on 'disentangling' spin and motional degrees of freedom at \( t_g = j2\pi/\delta \) ⇒ Residual spin-motional entanglement results in error action \(-iE_Q(t) = S_N(\alpha(t)a^\dagger - \alpha(t)^* a)\)

→ Key simplifications:

1. Ideal spin-flips (X gates) can be effected;
2. Target gate commutes with X;
3. Error action anti-commutes with X gate ⇒

\[
X Q \exp(-iE_Q) X Q \exp(-iE_Q) = Q^2 \quad \text{and} \quad Q^2 X \exp(-iE_Q) X \exp(-iE_Q) = Q^2
\]

→ 1st-order implementation of gate \( Q^2 \) ⇒ can iterate to achieve higher-order suppression...
II. Progress towards Optimized DCG Framework
Recap thus far...

The good... 😊

- CDCGs offer a proof-of-concept that arbitrarily accurate decoherence suppression solely based on open-loop control is possible in principle.
  - Highly portable – only need qualitative knowledge of environment and stretchable controls...
  - Fully analytical – rigorous performance analysis and [often] physical insight...
  - Can concatenate with composite pulses for robustness under systematic control errors...

The bad... 😞

- Ignoring the system Hamiltonian [driftless assumption] can be a serious oversimplification.
  - What if $H_S$ is required for universality and synthesizing primitive gates is non-trivial?...
  - How to construct balance pairs if the relationship between errors and control is not manifest?...

The ugly... 😞

- CDCG constructions can be very inefficient...
  - Single qubit, $n=1$: Sequence length grows exponentially with concatenation level...
  - Multiple qubits, $n$: Sequence length typically [also] grows exponentially with system size...

\[ G^{[m]} \equiv G_{adv} \simeq (\mathbb{Z}_2 \times \mathbb{Z}_2)^{\times n} \Rightarrow G_{adv} = 4^n, \quad L_{adv} = 2, \quad \chi_{adv} = 4^n \times 5 \]
For a given target gate, the actual control outcome is partitioned into ideal and error action:

→ Actual gate propagator over duration $T$:

$$ U(T) = T\exp \left\{ -i \int_0^T ds \left[ H_{ctrl}(s) + H_{S,g} + H_{err} \right] \right\} = Q \exp \left(-i E_Q \right) $$

CDCG framework provides a constructive recipe for finding a solution to

1. $ Q e^{i \phi} - T\exp \left\{ -i \int_0^T ds \left[ H_{ctrl}(s) + H_{S} \right] \right\} = 0 $ \hspace{1cm} \text{Gate synthesis}

2. $ \text{mod}_B (E_Q) \propto \tau^m + O(\tau^{m+1}) $ \hspace{1cm} \text{Error cancellation}

provided that (1) perfect [universal] gate synthesis can be achieved if $H_{err} = 0$, and (2) a systematic relationship can be found between control and error for each segment.

The more detail is available about error model and control specification, the lesser the need for portable DCG constructions ⇒ \textbf{Optimize for specific control scenarios}.

\textbf{Numerically optimized CDCGs}: Rely on numerical search methods to solve one/both the above equations, by restricting solutions [control variables] within the admissible domain.

→ Similar in spirit to strongly modulating pulses, OCT approaches...
Address the two problems separately [for now] – **Problem 1**: Retain driftless assumption...

**Strategy:** Exploit freedom in describing control profiles to optimize parametrically EPG.

1. Choose a desired pulse shape and parametrization – e.g., rectangular.
   \[
   Q([h_1, \tau_1]) = Texp[-i \int_0^T ds \ H_{ctrl}(s)] = \prod_{l=1}^n \exp[-i h_l H_l \tau_l], \quad T = \sum_{l=1}^n \tau_l
   \]

   ✓ Gate synthesis is automatically accommodated.

2. Obtain symbolic expansion of error action \( E_Q \) in terms of perturbative error operators.
   ✓ For a given sequence, error can be evaluated parametrically order-by-order.

3. Search numerically for parameters that cancel prefactor for each algebraically independent term, while implementing desired gating action:

   E.g., for 2nd-order DCG:
   
   \[
   mod_B(E_Q^{(2)}) \propto \tau^3 + O(\tau^4) \Rightarrow
   \]

   \[
   \begin{cases}
   z_1 \equiv mod_B(E_Q^{(1)}([h_l, \tau_l]]) = 0 \\
   z_2 \equiv mod_B(E_Q^{(2)}([h_l, \tau_l]]) = 0
   \end{cases}
   \]

   The existence of arbitrary-order DCGs guarantees existence of a solution to search problem.

   ➔ Explicit expressions for \( z_1 \) and \( z_2 \) depend on problem specification...
Illustrative results

→ Case study: Single qubit coupled to purely dephasing spin bath

\[ H_{error} = I_S \otimes \sum_{k=1}^{N} D_k \tilde{I}_k \cdot \tilde{I}_i + \sigma_z \otimes \sum_{k=1}^{N} A_k I_k z, \quad N = 5 \]

Recall:

\[ \tau_{m+1} = \left[ G_m L_m + 3 + (G_m - 1)(1 + 2^{1/(m+1)}) \right] \tau \]

→ Analytical generic DCG:

\[ \tau_2 = (14 + 3 \sqrt{2})20 \tau \approx 365 \tau \]

→ Analytical simplified DCG:

\[ \tau_2 = (14 + 3 \sqrt{2})8 \tau \approx 146 \tau \]

→ Numerically optimized DCG:

\[ \tau_2 \approx 21 \tau \]
Accommodating drift via robust optimization

Address the two problems separately [for now] – Problem 2: Focus on first-order DCGs...

Strategy: Search for simultaneous solution to gate synthesis and error cancellation conditions.

→ Simplest setting: Single qubit, [effectively] closed system, piecewise-const controls:

\[ H_{tot} = H_S + H_{err} + H_{ctrl}(t) = \omega \sigma_z + \epsilon \sigma_z + h(t) \sigma_x \]

Relevant to singlet-triplet qubit in DQD: \( \omega \) → magnetic field gradient, \( h(t) \) → exchange splitting


→ Drift is required for complete controllability but prevents a simple relationship between duration of each control segment and associated error action to be found...

✔ Cannot simply redefine \( H'_{err} = H_{err} + \omega \sigma_z \) – need not be small... only \( x \)-direction controllable...

Objective: Determine control solution that cancels [minimizes] simultaneously

1) Fidelity loss in the absence of error (gate synthesis) ⇒ \( z_1([h_i, \tau_i]) = \|U_{ctrl}(T) - Q\|\)

2) Effect of error Hamiltonian up to the 1st-order in \( \varepsilon \) ⇒ \( z_2([h_i, \tau_i]) = \|E_{Q}^{[1]}\|\)

(Simplest choice) \( z([h_i, \tau_i]) = z_1([h_i, \tau_i]) + z_2([h_i, \tau_i]) \)
Illustrative results

→ 'Twice easier' to synthesize gate vs. synthesizing a robust [1st-order DCG] gate:
  Minimization of \( z_j \) alone \( \Rightarrow \) 4 control segments suffice \( [z_j^{\text{min}} = 2.3 \cdot 10^{-8}] \)
  Minimization of \( z_j + z_2 \) \( \Rightarrow \) At least 8 control segments required \( [z^{\text{min}} = 2.0 \cdot 10^{-7}] \)

\[ Q = \exp \left( -i \frac{\pi}{8} \sigma_x \right) \]

→ 'Flatness' of DCG solution indicates its robustness compared to optimized gate
  Optimized gate has higher fidelity in the limit \( \epsilon \to 0 \quad [\epsilon < 10^{-8}] \)
  DCG provides higher fidelity in a wide range \( \epsilon > \epsilon_{\text{min}}, \epsilon_{\text{min}} T = O \left( z_1^{\text{min}} / z_2^{\text{min}} \right) \quad [\epsilon_{\text{min}} \approx 10^{-4}] \)
**Conclusion**

- DQEC – DD plus CDCGs – has the potential to reduce memory and gate errors below the level required by accuracy threshold for non-Markovian QEC.
  
  See also Ng, Lidar & Preskill, PRA 2011.

  ➔ Make contact with filter-function formalism for classical noise settings...
  

  ➔ Explore DCGs with continuous driving fields...
  

- Plenty of room exists for improving the efficiency of CDCG constructions and for optimizing their performance under specific system/control assumptions.
  
  ✔ Single-qubit setting:
  
  ➔ Develop comprehensive numerically-optimized solution, make formal contact with OCT (analyze complexity, landscape and convergence properties) ...

  ✔ Many-qubit setting:
  
  ➔ Need to better exploit locality and sparsity of physical error models...

- Dedicated experimental realizations/benchmarking of DCGs needed...

Stay tuned...
Quantum Firmware Collaboration

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