Experimental noise filtering by quantum control

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Extrinsic interference is routinely faced in systems engineering, and a common solution is to rely on a broad class of filtering techniques to afford stability to intrinsically unstable systems or isolate particular signals from a noisy background. Experimentalists leading the development of a new generation of quantum-enabled technologies similarly encounter time-varying noise in realistic laboratory settings. They face substantial challenges in either suppressing such noise for high-fidelity quantum operations\textsuperscript{1} or controllably exploiting it in quantum-enhanced sensing\textsuperscript{2–4} or system identification tasks\textsuperscript{5,6}, due to a lack of efficient, validated approaches to understanding and predicting quantum dynamics in the presence of realistic time-varying noise. In this work we use the theory of quantum control engineering\textsuperscript{7,8} and experiments with trapped \textsuperscript{171}Yb\textsuperscript{+} ions to study the dynamics of controlled quantum systems. Our results provide the first experimental validation of generalized filter-transfer functions casting arbitrary quantum control operations on qubits as noise spectral filters\textsuperscript{8,10}. We demonstrate the utility of these constructs for directly predicting the evolution of a quantum state in a realistic noisy environment as well as for developing novel robust control and sensing protocols. These experiments provide a significant advance in our understanding of the physics underlying controlled quantum dynamics, and unlock new capabilities for the emerging field of quantum systems engineering.

Time-varying noise coupled to quantum systems—typically qubits—generically results in decoherence, or a loss of ‘quantuness’ of the system. Broadly, one may think of the state of the quantum system becoming randomized through uncontrolled (and often uncontrollable) interactions with the environment during both idle periods and active control operations (Fig. 1a). Despite the ubiquity of this phenomenon, it is a challenging problem to predict the average evolution of a qubit state undergoing a specific, but arbitrary operation in the presence of realistic time-dependent noise—how much randomization does one expect and how well can one perform the target operation? Making such predictions accurately is precisely the capability that experimentalists require in realistic laboratory settings. Moreover, this capability is fundamental to the development of novel control techniques designed to modify or suppress decoherence as researchers attempt to build quantum-enabled technologies for applications such as quantum information and quantum sensing.

These considerations motivate the development of novel engineering-inspired analytic tools enabling a user to accurately predict the behaviour of a controlled quantum system in realistic laboratory environments. Recent work has demonstrated that the average dynamics of a controlled qubit state evolution may be captured using filter-transfer functions (FFs) characterizing the control. The fidelity of an arbitrary operation over duration $\tau$, $F_{\text{exp}}(\tau) \propto e^{\int_0^\tau \text{d}t \text{FF}(\omega)}$, is degraded owing to frequency-domain spectral overlap between noise in the environment given by a power spectrum $S(\omega)$, and the filter-transfer functions denoted $F(\omega)$ (Methods)\textsuperscript{11–14}.

The FF description of ensemble-average quantum dynamics tremendously simplifies the task of analysing the expected performance of a control protocol in a noisy environment as it permits consideration of control as noise spectral filtering. The FFs themselves may be described using familiar concepts such as frequency passbands, stopbands and filter order, enabling a simple graphical representation of otherwise complex concepts in the dynamics of controlled quantum systems (Fig. 1b). Noise filtering, in practice, is achieved through construction of a control protocol (Fig. 1a) which modifies the controllability of the quantum system by the noisy environment over a defined frequency band. Adjusting $F(\omega)$ and changing its overlap with the noise spectrum thus allows a user to change the average dynamics of the system in a predictable way.

To see the importance of this capability we may consider the various tasks that might be of interest in experimental quantum engineering and the role of noise spectral filtering in these applications. In quantum information an experimentalist may aim to suppress broadband low-frequency noise to maximize the fidelity of a bounded-strength quantum logic operation (Fig. 1b, upper trace), and then calculate the residual error. Alternatively, in quantum-enabled sensing or system identification he or she may perform narrowband spectral characterization of a given operation (Fig. 1b, lower trace), where any change in the measured fidelity under filter application represents the signal of interest\textsuperscript{6,16}.

The intuitive nature of this framework is belied by the challenge of calculating FFs for arbitrary control protocols, generally involving time-domain modulation of control parameters such as the frequency and amplitude of a driving field. The nature of quantum dynamics means that the implemented control framework is generally nonlinear; for instance, one finds complex dynamics in circumstances where the noise and control operations do not commute, such as a driven operation $(\propto x \sigma_z)$ in the presence of dephasing noise $(\propto \sigma_z)$. Recent theoretical effort has allowed calculation of FFs for arbitrary single-qubit control and arbitrary universal classical noise\textsuperscript{10}, expanding significantly beyond previous demonstrations restricted to the identity operator in pure-dephasing environments\textsuperscript{15}. It

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is this more general case where the impact of noise filtering and the FFs may have the most significant impact on the quantum engineering community, and where experimental tests are vital.

In our experimental system, based on the 12.6 GHz qubit transition in $^{171}\text{Yb}^+$ (Supplementary Methods), we are able to perform quantitative tests of operational fidelity for arbitrary control operations; these may then be compared against calculations of $F_\tau(\tau)$ as a fundamental test of FF validity. A key tool in our studies is bath engineering, in which we add noise with user-defined spectral characteristics to the control system, producing well-controlled unitary dephasing or depolarization.

As a first example (Fig. 1c), experimental measurements of operational fidelity for a $\pi$, pulse driving qubit population from the dark state to the bright state, $|0\rangle \rightarrow |1\rangle$, in the presence of engineered time-dependent dephasing noise give good agreement with analytic calculation of $F_\tau(\tau)$ using the noise power spectrum and analytic FFs (ref. 10) with no free parameters (Methods). This approach therefore immediately demonstrates the predictive power of the FF formalism.

The FFs for much more complex control, such as compensating composite pulses, can be calculated and experimentally validated as well (Fig. 1e). These protocols are commonly used in nuclear magnetic resonance and electron spin resonance in attempting to suppress static offsets in control parameters such as the frequency of the drive inducing spin precession. Calculating the FFs for these protocols now reveals their sensitivity to time-dependent noise—an important characteristic for deployment in realistic quantum information settings. We experimentally demonstrate a form of quantum system identification (Methods), effectively calculating the amplitude-noise filter functions, $F_\tau(\omega)$, for two well-known compensating pulse sequences known by the shorthand designations SK1 and BB1 (Supplementary Methods). Again, calculations of $F_\tau(\tau)$ match data well over the entire band in the weak-noise limit (Fig. 1f) with no free parameters.

Our choice of characterizing these compensating pulse sequences highlights an important issue in the prediction of ensemble-average dynamics of controlled quantum systems. Ultimately, the underlying physical principles giving rise to the analytic form of $F(\omega)$ are based on the well-tested average Hamiltonian theory exploited in crafting these pulses. Despite this shared theoretical foundation, the calculation of spectral filtering properties is quite distinct from calculation of quasi-static error terms in a Magnus expansion, with important consequences for average quantum dynamics in realistic time-varying noise environments.

Accordingly, our tests of the FF formalism reveal that compensating pulses designed to suppress errors to high order in a Magnus-expansion framework need not be efficient noise spectral filters (Supplementary Methods and ref. 19). Despite significant differences in their construction—the BB1 protocol is designed to provide higher-order cancellation of Magnus terms than SK1—both of the selected composite pulses provide similar filtering of time-dependent noise, given by the filter order (slope of the FF in Fig. 1e). In the weak-noise limit frequency-domain characteristics...
These simple but powerful validations of the predictive power of the generalized FF formalism now open the possibility of demonstrating the construction of noise filters with a specified spectral response, employing the filter-transfer functions as key analytic tools. Filters may take a wide variety of forms as needed by users—including high-pass filters for broadband noise suppression and band-stop filters useful for narrowband noise characterization (Fig. 1b).

In the discussion that follows, we focus on a common setting in which we aim to improve operational fidelity by reducing the influence of broadband non-Markovian noise on a target state transformation. Filters are realized as $n$-step sequences of time-domain control operations with tunable pulse amplitude and phase, similar in spirit to compensating composite pulses in NMR (refs 17–19), dynamically corrected gates (DCGs) in quantum information21–23, and open-loop modulated pulses in quantum control24–26. However, recalling the difference between Magnus cancellation order and filtering order described above, in this setting we wish to synthesize a filter with arbitrary, user-defined spectral characteristics captured by a cost function, $A(\Gamma_n)$, to be minimized for a filter represented by $\Gamma_n(\theta_1, \tau_1, \phi)$ (Fig. 2b,c and Methods).

To provide efficient solutions to filter design we restrict our control space and focus on constructions synthesized using concepts from functional analysis in the basis set of Walsh functions—square-wave analogues of the sines and cosines27,28 (Fig. 2a). This approach provides significant benefits for our problem29, but is by no means the only basis set for composite filter construction23–28.

As an example we synthesize noise filters via weighted linear combinations of Walsh functions, PA$\ell_0(\pi c)$ denoted by the Paley-ordered index, $k$. These filters are designed to suppress time-varying dephasing noise over a low-frequency stopband while implementing a bounded-strength driven rotation about the $x$ axis on the Bloch sphere (Supplementary Methods). In this case the Walsh-synthesized waveform dictates an amplitude modulation pattern for the control field over discrete time segments. Importantly, Walsh filter synthesis is compatible with pulse segments possessing arbitrary pulse envelopes, including sequences of, for example, square (used here) or Gaussian pulse segments (Fig. 2b).

Analytic design rules provide simple insights into how one may craft effective modulation protocols, and a Nelder–Mead simplex optimization is used to find high-performing operations as defined by our cost function. Relative to an unfiltered primitive gate, the dephasing filter function, $F_\pi(\omega)$, for the simplest four-pulse construction $W_1$ shows increased steepness in the stopband (Fig. 2c, red), reducing $A(\Gamma_n)$ (here the gate performs $\theta = \pi$). This measure of filter order may be further increased via construction $W_2$, in turn reducing the cost function for optimization (blue shaded area in Fig. 2c). Relating back to earlier demonstrations of filter order in compensating pulses, $W_2$ presents an interesting case of a high-order noise filter over the target band which provides only first-order Magnus cancellation.

Filters $W_1$ and $W_2$ are representative, rather than unique solutions. In Fig. 3b we show the calculated cost function, $A(\Gamma_n)$, as a function of the Walsh coefficients used in constructing $W_1$, $X_0$ and $X_1$, giving the modulation profile indicated in Fig. 3a. Blue areas meet our minimized target, indicating useful filters, revealing a wide variety of possible constructions with favourable characteristics. Experimental tests of these protocols reveal that Walsh-modulated waveforms minimizing $A(\Gamma_n)$ effectively suppress noise in the designated stopband for arbitrary rotation angles (Fig. 3c–e), and outperform standard pulses in the small-error limit germane to quantum information (Fig. 3f). See Methods.

Our focus has been on providing a validated framework for the vital task of predicting quantum dynamics in realistic environments and demonstrating the relevant physics through construction of noise spectral filters. The Walsh-modulated filters
presented here—based on the achievable frequency-domain filter order—complement existing techniques rather than attempting to provide optimal-performance error-robust gates. Our results on high-pass noise filters, for instance, add to existing compensating pulse sequences designed for quasi-static noise, as well as gate constructions with interleaved dynamical decoupling that seek toperiodically ‘refocus’ quantum evolution\(^{29-32}\).

Importantly, recent work has demonstrated that the filter-transfer function formalism is applicable to multi-qubit settings where dynamics may be considerably more complex than the single-qubit case\(^{33-35}\). In addition, ongoing efforts suggest there exists a path towards further extension of the generalized filter-transfer function and noise filtering formalisms to arbitrary control settings involving multiple qubits subject to general noise from non-Markovian classical and/or quantum mechanical environments. We believe that with the validations provided here, this simple extensible framework with precise predictive power will provide a path for experimentalists to characterize and suppress the effects of noise in generic quantum coherent technologies, ultimately enabling a new generation of engineered quantum systems.

**Methods**

The fidelity of a control operation for a single qubit in the presence of a time-dependent environment is reduced as \( F(t) = 1/2 (1 + e^{-\Delta t}) \), where \( \Delta t = \tau \sum_j | \omega_j \omega_j | \Delta \omega_j \delta \omega_j F(\omega_j) \), and \( \tau \) is the total duration of the operation. In this expression for fidelity, the integral considers contributions from independent noise processes through their frequency-domain power spectra \( S(\omega) \), \( \omega \in \{z, X_0, \cdots \} \), capturing dephasing along \( \hat{z} \) and amplitude noise along \( \hat{X_0} \). To first order for small \( \Delta t \), the fidelity can be approximated as the product of the individual transfer functions, each denoted by \( F(\omega) \).

Experimental measurements involve state initialization in \(| 0 \rangle \) followed by a control operation—or series of control operations—designed to drive qubit population from the dark state to the bright state, \(| 1 \rangle \rightarrow | 0 \rangle \). For instance, tests of filters used for rotations \( \theta < \pi \) are repeated sequentially such that the net rotation enacted while varying \( \theta \) is \( 2 \pi \) \( \theta \). In experiments we always perform a net \( \pi \) rotation \( | 0 \rangle \rightarrow | 1 \rangle \) by sequentially performing identical copies of rotations for \( \theta < \pi \).

Figure 3 | Construction of the first-order Walsh amplitude-modulated dephasing-suppressing filter. a. Schematic representation of Walsh synthesis for a four-segment amplitude-modulated filter (WAMF). Walsh synthesis can be used to determine either the modulating envelope of square pulse segments, or the net area of discrete Gaussian pulses with differing amplitudes. b. Two-dimensional representation of the integral metric defining our target cost function, \( A(\Omega) \), integrated over the stopband \( \omega \in (10^{-9}, 10^{-4}) \) \( \tau \). Areas in blue minimize \( A(\Omega) \), representing effective filter constructions. The \( X_0 \) parameter determines the net rotation enacted in a gate while \( X_0 \) determines the modulation depth, as represented in a. White lines indicate possible constructions for filters implementing rotations of \( \theta = \pi / 2 \) and \( \theta = \pi / 4 \) from top to bottom. c-f. Experimental measurements of gate infidelity (infidelity \( 1 - F \)) for rotations constructed from various Walsh coefficients in the presence of engineered noise (Fig. 2d-g). Black dots in line are calculated fidelity by Schrödinger equation integration (raw and smoothed respectively). All values of \( X_0 \) for a given \( X_0 \) implement the same net rotation, indicated by a control experiment with no noise. Total rotation time is scaled with \( X_0 \) to preserve a maximum Rabi rate. Black dashed line (right axis) corresponds to \( A(\Omega) \) from a. In experiments we always perform a net \( \pi \) rotation \( | 0 \rangle \rightarrow | 1 \rangle \) by sequentially performing identical copies of rotations for \( \theta < \pi \).

Randomized benchmarking results (50 randomizations) demonstrating superior performance of a modulated gate in the small-error limit (infidelity \( 0.5\% \) per gate), see Supplementary Methods.
we perform a driven operation generating a rotation through an angle \( \theta = \int_0^T \Omega(t) \, dt \) about the axis \( \mathbf{r} = (\cos(\phi), \sin(\phi), 0) \), with \( \Omega(t) \) the Rabi rate over the 4th pulse segment.

The value of \( n \) is chosen to be a power of two, compatible with synthesis over discrete-time Walsh functions. The Walsh functions are piecewise-constant over segments which are all integer multiples of base period \( \tau \). This approach brings benefits for the current setting; for instance, their piecewise-constant construction builds intrinsic compatibility with discrete clocking and classical digital logic, while the well-characterized mathematical properties of the Walsh functions provide a basis for establishing simple analytic filter-design rules, and flexibility in realizing a wide variety of filter forms.

For the filters W1 and W2 presented in the main text, Walsh-synthesis design rules dictate that we implement our filtered rotation by \( \theta \), over a minimum of four discrete steps, permitting synthesis over \( \mathcal{PA}_m \) to \( \mathcal{PA}_0 \). Within this small set, the coefficient of \( \mathcal{PA}_0 \), denoted \( X_0 \), sets the total rotation angle \( \theta \mod 2\pi \) for the modulated driven evolution, and only non-zero \( X_0 \) preserves symmetry. We experimentally test the performance of four-segment amplitude-modulated filters by scanning over \( X_0 \) for fixed \( X_1 \) (denoted by white dotted lines in Fig. 3b). Values of \( X_0 \), minimizing \( A(\Gamma_0) \) (dips in the dashed trace, right axis) also minimize the experimentally measured infidelity in the presence of engineered low-frequency noise (open circles, left axis). This behaviour is observed for various target rotation angles of interest (Fig. 3c–e), with predicted shifts in the optimal values of \( X_0 \) with changes in \( X_0 \) borne out through experiment. Filter W2 is constructed over \( \mathcal{PA}_m \) to \( \mathcal{PA}_0 \), and has twice as many m subscripts as W1. Interestingly, W1 is a special case of an analytically constructed dynamically corrected NOT gate (a \( \pi \)-rotation)\(^\text{21}\). For details of the Walsh functions, Walsh synthesis and Walsh-basis analytic design rules see Supplementary Methods.

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Author contributions

A.S., H.B., D.H. and M.I.B. conceived and performed the experiments, built experimental apparatus, contributed to data analysis and wrote the manuscript. T.J.G. conceived the relevant theoretical constructs. J.S., M.C.J. and X.Z. assisted with development of the experimental system and data collection. J.F.M. assisted with data collection.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.I.B.

Competing financial interests

The authors declare no competing financial interests.