Exact voltage pulse engineering for the collective unitary control of semiconductor quantum dot spin qubit processors

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We present a method of voltage pulse design for the optimal control of spin qubits in a linear array of quantum dots (Fig. 1). Voltage pulses are reverse-engineered from the voltage-dependent spin Hamiltonian parameters: g-factor deviations $\delta g_i(\boldsymbol{V}, \boldsymbol{W})$ and exchange couplings $J_i(\boldsymbol{V}, \boldsymbol{W})$, when their pulse shapes $S(t)$ are constrained to ensure time-ordered evolution [2]. We show that a single numerical integration of a system of ODEs of type $d[\boldsymbol{V}, \boldsymbol{W}]/dS = \boldsymbol{F}(\boldsymbol{V}, \boldsymbol{W})$ enables one to reconstruct voltage pulses $V_i(S(t))$, $W_i(S(t))$ for any shape function chosen for the spin Hamiltonian controls. The procedure yields pulses for single-qubit rotations in the global ESR field, SWAP$^{k/2}$, or Control-Phase gates, with theoretically perfect unitary fidelities. Additionally, we develop strategies to reduce the number of necessary voltage controls such as using a frequency-modulated rotating frame. The controls shown in Fig. 2 demonstrate simultaneous multi-qubit operations while holding tunneling gate voltages fixed. These approaches open a pathway to simplifying experimental devices without compromising their controllability.

References

[1] Buonacorsi, Brandon, et al. Quantum Science and Technology 4.2 (2019) 025003.

[2] Khromets, Bohdan, Zach D. Merino, and Jonathan Baugh. *arXiv:2402.08146* (2024).

Figures

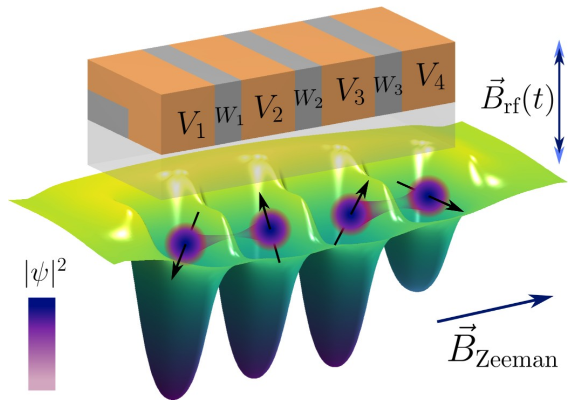

Figure 1: Schematic of a spin qubit computational node of a network architecture proposed in [1]. The plunger gate voltages $V_{1\text{-}4}$ (golden) accumulate electrons in the electrostatic potential wells (green), and the tunnelling gate voltages $W_{1\text{-}3}$ (silver) control the tunnelling barriers. All spins are coupled to the global Zeeman and RF magnetic fields (blue) for electron spin resonance (ESR). Quantum logic operations on many-electron states (purple) are realized through the combined control of ESR magnetic field and voltage-dependent g-factors and exchange couplings.

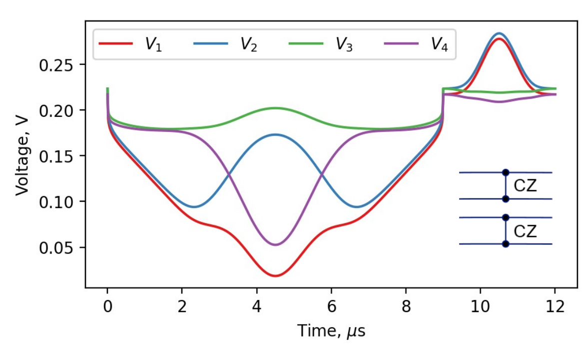

Figure 2: Voltage pulses realizing simultaneous Control-Z operations on 4 qubits from Fig. 1 with no explicit tunnel barrier control ($W_{1\text{-}3} \equiv 0$), designed in a frequency-modulated rotating frame. The unitary fidelity of such an operation can be made arbitrarily close to 1 by increasing the precision of the ODE solver.