# Quantum Control of Generic Quantum Systems and Nanostructures for Quantum Technologies: Different Approaches

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## ABSTRACT

Quantum control methods, like rapid adiabatic passage, stimulated Raman adiabatic passage, shortcuts to adiabaticity and optimal control, have become an integral part of modern quantum technologies, for example quantum computation and quantum sensing, since they are exploited in order to find the optimal pulse-sequences which drive quantum systems to the desired target state in minimum time or with maximum fidelity, overcoming the undesirable environmental interactions which lead to decoherence and dissipation. In this paper we quickly present our recent research activities regarding the control of generic quantum systems and nanostructures, and briefly discuss the possibility to use reinforcement learning as an alternative method for quantum control.

## CCS CONCEPTS

• **Computing methodologies → Computational control theory**; **Neural networks**; **Quantum mechanic simulation**; • **Hardware → Quantum error correction and fault tolerance**.

## KEYWORDS

optimal control, quantum control, reinforcement learning, quantum computation

## 1 INTRODUCTION

The development of quantum computation and many other quantum technology applications, like quantum metrology and quantum sensing, rely on the precise control of the basic quantum elements, the two-level quantum systems and three-level quantum systems, and the creation of the necessary quantum gates and entanglement with high fidelity and robustness. Several methods have been developed over the years to succeed this purpose. A basic category composes of adiabatic methods, like rapid adiabatic passage [1] and stimulated Raman adiabatic passage (STIRAP) [2], which give efficient and robust control against moderate variations of system parameters but require long times for the adiabatic transfer, which, in general, leads to a degraded performance in the presence of undesirable interactions with the environment (decoherence effects). Another important category that has been extensively studied in the last decade includes several methods collectively referred to as shortcuts to adiabaticity [3]. Their main concept is to bring the quantum system to the same final state as the adiabatic methods in shorter time; some of these methods simply bypass the intermediate adiabatic states, while others add an extra term in the system's Hamiltonian, which cancels the diabatic transitions and allows the quantum system to evolve along the adiabatic trajectory of the original Hamiltonian. A third basic method is based on optimal control [4] of the quantum systems, where optimizations are performed against system parameters, like, for example, minimum evolution time or minimum pulse energy for performing a specific quantum transfer with maximum fidelity. Our group has presented several applications using the above methodologies in the quantum control of either generic quantum systems or specific quantum nanostructures, see e.g. Refs. [5–12]. A summary of the above results will be presented here. More recently, a different approach for quantum control has been presented by applying deep reinforcement learning techniques for the robust and high efficiency control of quantum evolution [13–15]. Our research plans in this area will also be discussed.

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## 2 QUANTUM CONTROL METHODS

### 2.1 Adiabatic Passage Methods

The basic unit appearing in most modern quantum technologies is the two-level system or qubit and several methods have been developed for controlling the states of qubits. One of the simplest is the resonant $\pi$-pulse. Using the familiar nuclear magnetic resonance (NMR) terminology, this pulse is resonant with the frequency of the two-level system, is applied along the transverse direction ($x$ or $y$), and its amplitude and duration are such that it rotates the qubit state from up ($+z$) to down ($-z$) or vice versa. The drawback of this method is that imperfections in the pulse amplitude or duration, or even uncertainties in the quantum system, may degrade the fidelity of population inversion.

A more robust method is the so-called adiabatic passage. Now the qubit control is achieved using the longitudinal field, which is gradually changed from the up- to down-direction. If the change is slow enough (adiabatic), then the qubit state follows the instantaneous magnetic field and population inversion is accomplished. Closely related to adiabatic passage is the method of stimulated Raman adiabatic passage (STIRAP), applied to three-level quantum system in the lambda or ladder configuration. The goal is to transfer population from some initial to a final target state, without direct coupling between them, through a lossy indermediate state, which is coupled to the other two states with properly selected pulses. This task is accomplished by applying the pulses in a counterintuitive order, where the pulse coupling the intermediate and target states is applied before the pulse coupling the initial and intermediate states. If the change in the applied fields is again slow enough (adiabatic), then the population transfer is accomplished through a temporary eigenstate of the system, which initially coincides with the starting state while at the end coincides with the target state. This method is also known to be robust in moderate variations of the fields or other experimental parameters.

## 2.2 Shortcuts to Adiabaticity

The drawback of adiabatic passage methods is the long necessary times, in order to satisfy the adiabatic approximation, leading to a degraded performance in the presence of undesirable environmental interactions which cause dissipation and dephasing in quantum systems. In order to overcome this problem and accelerate quantum adiabatic evolution, several methods have been proposed, collectively known as *shortcuts to adiabaticity*. Two major approaches can be distinguished among these methods. In the first approach, the main idea is to reach the same final state as with a slow adiabatic process, but without necessarily following the adiabatic path during the whole time. In the second approach, an extra Hamiltonian is added to the original Hamiltonian so the system, under the influence of the total Hamiltonian, can follow the eigenstates of the original (reference) Hamiltonian even for very fast evolutions. The extra *counterdiabatic* Hamiltonian cancels the diabatic terms arising for short evolutions when the reference Hamiltonian is transformed to the adiabatic basis.

In our recent works [5–7, 10] we have successfully used both methods in order to efficiently control various quantum systems. Specifically, we have used the first approach in order to maximize entanglement in a bosonic Josephson junction [5], between exciton-polaritons [6], and coupled spins [7], while we have evaluated the performance of the method for the three-level STIRAP system under the presence of Ornstein-Uhlenbeck noise processes in the energy levels [10].

## 2.3 Optimal Control

Optimal control theory [4] was developed during the cold war to answer questions related to the space race, for example what is the minimum-fuel trajectory to the moon. Through the years it has found a broad range of applications in a variety of systems including aerospace, electrical, biomedical and nuclear, but also has been successfully applied in quantum systems. In the quantum context, usually the goal is to find the electromagnetic field which can drive a quantum system from some initial state to a desired target state, in the minimum possible time or with maximum fidelity, reducing thus the unwanted effect of noise.

For low-dimensional quantum systems, for example two- or three-level systems, analytical methods like Pontryagin's Maximum Principle [4] have been successfully used to calculate the optimal pulses. For more complicated systems with larger number of states, it is often necessary to recourse to numerical optimization. Numerical optimal control methods are divided into two major groups, gradient algorithms and direct methods. The methods of the first group have a high accuracy and assure that the obtained solution satisfies the necessary optimality conditions. But they also present several drawbacks. For example, one needs to calculate the gradients of the problem by hand. Additionally, the radius of convergence is usually small, thus a good initial guess is needed. A similar guess is also necessary for the Lagrange multipliers. In the direct methods on the other hand, the continuous optimal control problem is discretized in time and is eventually transformed to a nonlinear programming problem with thousands of variables, which nevertheless can be solved by using commercially available software programs. The drawback of direct methods is that they are not as accurate as the gradient methods, but they have a larger radius of convergence and there is no need to initially guess the Lagrange multipliers. In our research works involving computational optimal control, we use the optimal control solver BOCOP [16], implementing a direct method. Some very useful practical characteristics of BOCOP are that it can easily incorporate constraints on the state and control variables, while the control functions can be expressed in terms of trigonometric series.

In our recent work [8, 9] we used optimal control theory to accelerate adiabatic passage in a two-level system, and derived a modified Roland-Cerf protocol, where recall that the original Roland-Cerf quantum protocol was developed in order to accelerate Grover's quantum search algorithm. We have also used numerical optimal control in some of the entanglement generation problems discussed above [5, 7], as well as for the more efficient generation of single photons from a bosonic Josephson junction [11]. The BOCOP program was also used for the fast initialization of the spin in a composite nanostructure, made of a quantum dot in the Voigt geometry coupled to a transition metal dichalcogenide monolayer [12].

## 2.4 Quantum Control with Reinforcement Learning

Deep reinforcement learning techniques have been recently employed in order to efficiently control quantum systems, with examples including among others many body quantum systems [13], quantum gates [14], and coherent transport of quantum states in a STIRAP-like quantum system [15]. The advantage of reinforcement learning compared to the previously discussed control methods appears to be that the neural network, whose output are the control fields, can be trained in the presence of realistic noise processes. As a result, the control fields obtained using reinforcement learning can achieve better fidelities than the other methods under realistic noise conditions.

Our ongoing research efforts are concentrated to apply deep reinforcement learning in quantum systems where coherently controlled adiabatic passage methods (coherently controlled STIRAP) are used, for example quantum systems where continuum of states are involved [17], quantum control of degenerate states [18], and purification of mixtures of right-handed and left-handed chiral molecules [19, 20]. We intend to apply this method not only in model quantum systems but also in real molecules and nanostructures [21]. We also expect reinforcement learning to be particularly suitable for computationally demanding quantum control applications, like for example the control of large chains or arrays of coupled qubits [22]. It is our furthest ambition to apply this method in such systems.

## 3 CONCLUSION

We have briefly presented our recent an ongoing efforts regarding the control of quantum systems using various methodologies, and discussed the challenge to enrich our computational arsenal using the powerful technique of deep reinforcement learning.

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