Front. Phys. China (2006) 3: 256－262
DOI 10.1007/s11467-006-0032-x

REVIEW ARTICLE

DONG Dao-yi, CHEN Zong-hai, ZHANG Chen-bin, CHEN Chun-lin

Feedback control of quantum system

Abstract Feedback is a significant strategy for the control of quantum system. Information acquisition is the greatest difficulty in quantum feedback applications. After discussing several basic methods for information acquisition, we review three kinds of quantum feedback control strategies: quantum feedback control with measurement, coherent quantum feedback, and quantum feedback control based on cloning and recognition. The first feedback strategy can effectively acquire information, but it destroys the coherence in feedback loop. On the contrary, coherent quantum feedback does not destroy the coherence, but the capability of information acquisition is limited. However, the third feedback scheme gives a compromise between information acquisition and measurement disturbance.

Keywords quantum feedback control, information acquisition, state recognition, coherence

PACS numbers 03.65.-w, 89.70.+c

1 Introduction

Control of quantum system is a most important task in atomic physics, molecular chemistry and quantum information [1－5]. Especially in the rapidly developing quantum information science [6], since information is represented with quantum bit (qubit) and quantum information processing is essentially the manipulation of quantum state, the ability to control quantum system at will is necessary. Hence quantum control theory rapidly develops in recent years, where it expects to determine how to drive quantum mechanical systems from an initial given state to a pre-determined target state with some given time T [7]. The current main fields of quantum control research include controllability [8－11], quantum optimal control [12－14], coherent control [15－17] and quantum feedback control [18－24]. The controllability answers whether a controller can drive a quantum system to a desired state. Some necessary and sufficient conditions on controllability of some finite-dimensional Hamiltonian quantum systems have been obtained. Quantum optimal control theory is applied to find the best control fields to achieve the desired target. Coherent control is a particularly powerful quantum control method and it has been widely applied to chemical reaction, especially selectively breaking and making chemical bonds in polyatomic molecules.

Moreover, quantum feedback control has interested many scientists. As we all know, feedback is a most effective strategy in classical control theory and the aim of feedback is to compensate the effects of unpredictable disturbances on a system under control, or to make automatic control possible when the initial state of the system is unknown. In quantum feedback, scientists expect to obtain information about the system, process the information and feed it back to the system to complete active control of quantum system in a desired way. To control a system, one must obtain the information about the state of system through measurement. However, a quantum system is essentially different from a classical one. The measurement on a classical system doesn't change its state, but commonly a measurement of a quantum system will disturb its quantum state. Hence quantum feedback control may have many characteristics different from classical feedback. The first theoretical work on quantum feedback was presented by Yamamoto *et al.* [19, 25], where they treated the fluctuations of the photocurrent in negative feed-

DONG Dao-yi, CHEN Zong-hai (✉), ZHANG Chen-bin,
CHEN Chun-lin
Department of Automation, University of Science and Technology of China, Hefei 230027, China
E-mail: chenzh@ustc.edu.cn

DONG Dao-yi
The present address: Key Laboratory of System Control, Academy of Mathematics and Systems Science, Chinese Academy of Science, Beijing 100080, China
E-mail: dydong@amss.ac.cn

Received June 15, 2006

back way to generate amplitude squeezed state. Since then, scientists have proposed many quantum feedback schemes such as Markovian quantum feedback [20], Bayesian quantum feedback [21], non-Markovian quantum feedback with time delay [22], coherent quantum feedback [23] and quantum feedback based on cloning and recognition [24]. In this paper, we review different quantum feedback control strategies and divide them into three classes according to the different methods of information acquisition: quantum feedback control with measurement, coherent quantum feedback control and quantum feedback control based on cloning and recognition.

This paper is organized as follows. In Section 2, we briefly introduce several information acquisition methods based on measurement including projective measurement, POVM measurement and QND measurement. Section 3 reviews some quantum feedback strategies with quantum measurement including Markovian quantum feedback, Bayesian quantum feedback and non-Markovian quantum feedback with time delay. In Section 4 and Section 5, we introduce coherent quantum feedback and quantum feedback based on cloning and recognition. Concluding remarks are given in Section 6.

2 Information acquisition in quantum feedback control

In quantum control, the systems to be controlled are mainly some quantum systems, whose states are called quantum states. According to quantum theory, the measurement on a quantum system will make its state collapse, which is the greatest difficulty for information acquisition in quantum feedback control. However, measurement is a main method for acquiring feedback information. Hence we will briefly introduce several quantum measurement including projective measurement, POVM measurement and QND measurement [26].

2.1 Projective Measurement

A projective measurement is described by an observable, M, a Hermitian operator on the state space of the system being observed [27]. The observable has a spectral decomposition,

$$M = \sum_m m P_m \tag{1}$$

where P_m is the projector onto the eigenspace of M with eigenvalue m. The possible outcomes of the measurement correspond to the eigenvalues, m, of the observable. Upon measuring the state $|\psi\rangle$, the probability of getting result m is given by

$$p(m) = \langle\psi|P_m|\psi\rangle \tag{2}$$

If the outcome m occurred, the state of the quantum system immediately after the measurement is $\dfrac{P_m|\psi\rangle}{\sqrt{p(m)}}$.

2.2 POVM Measurement

POVM stands for "Positive Operator-Valued Measure". Let's define

$$E_m \equiv M_m^+ M_m \tag{3}$$

where $\{M_m\}$ are the general measurement operators and satisfy the completeness equation:

$$\sum_m M_m^+ M_m = I \tag{4}$$

Thus E_m is a positive operator satisfying

$$\sum_m E_m = I \tag{5}$$

and

$$p(m) = \langle\psi|E_m|\psi\rangle \tag{6}$$

The operator E_m is a POVM element and the complete set $\{E_m\}$ is a POVM [27]. Here different operators E_m are not necessarily orthogonal, however, the operators P_m must be orthogonal in projective measurement.

In fact, POVM measurement is a kind of generalized quantum measurement. Under some certain circumstances, it is possible to get more information through POVM measurement than through projective measurement. However, projective measurement and POVM measurement inevitably destroy the quantum state to be measured. Hence some scientists show interest in quantum nondemolition (QND) measurement [28].

2.3 QND Measurement

Consider a system that has some observable $\hat{A}$. We define a QND measurement of $\hat{A}$ as a sequence of precise measurement of $\hat{A}$ such that the result of each measurement is completely predictable from the result of the first measurement-plus, perhaps, other information about the initial state of the system [29]. Quantum nondemolition measurements are ideal tools for use in the detection of weak external forces that act on the system. However, most observables cannot, even in principle, be monitored in a QND way. A general necessary and sufficient condition that $\hat{A}$ can be monitored in a QND way is that the QND meter must satisfy [28]:

$$[\hat{A}, \hat{U}]\,|\psi\rangle = 0 \tag{7}$$

where $|\psi\rangle$ is the initial state of the quantum meter and $\hat{U}$ is the operator of the joint evolution of the quantum meter and the object under study.

QND measurement is a kind of precise measurement and can be used to quantum feedback control [30]. Unfortunately, only some specific examples can use QND to acquire feedback information since only some specific observables are QND observables.

3 Quantum feedback control with measurement

Based on the discussion in Section 2, we know that quantum measurement generally destroys the state of system to be monitored. Even though measurement, as in classical feedback control, is still a main way for information acquisition in quantum feedback control. Hence quantum feedback control with measurement is first proposed. Since the first theoretical work on quantum feedback was presented [19, 25], some other quantum feedback strategies including Markovian quantum feedback [20], Bayesian quantum feedback [21] and non-Markovian quantum feedback with time delay [22] also have been proposed.

3.1 Markovian quantum feedback

Markovian quantum feedback scheme is first proposed by Wiseman and Milburn. In 1993, they presented a quantum theory of optical feedback via homodyne detection and solved the problem of quantum-limited optical cavity feedback for the case of instantaneous feedback of the homodyne photocurrent. In their quantum feedback theory, the homodyne photocurrent is immediately fed back onto optical cavity to alter the dynamics of the source cavity and may then be forgotten, so the master equation describing the resulting evolution is Markovian and the feedback scheme is called Markovian quantum feedback [20]. The feedback control system is an open system and its state can be described by density operator ρ. They obtained the general master equation for homodyne-mediated feedback [20]:

$$\dot{\rho} = -\mathrm{i}\,[H_0, \rho] + \boldsymbol{D}\,[a]\rho + \mathcal{K}\,(a\rho + \rho a^+) + \frac{1}{2\eta}\mathcal{K}^2\rho \qquad (8)$$

where H_0 is internal Hamiltonian, a and a^+ are annihilation operator and creation operator respectively, and $\boldsymbol{D}\,[a]$ is a superoperator satisfying

$$\boldsymbol{D}\,[a]\rho = a\rho\, a^+ - \frac{1}{2}\,(a^+ a\rho + \rho\, a^+ a) \qquad (9)$$

$\mathcal{K}$ is a Liouville superoperator satisfying $\mathcal{K}\rho\mathcal{K} = -\mathrm{i}\,[A, \rho]$ for arbitrary Hermite operator A, and η is the efficiency of the detection system.

This feedback scheme has been applied to lock the phase of a regularly pumped laser and the result shows that it can produce perfect squeezing on resonance in the output light [20, 31]. It is also used to complete some other tasks such as stabilizing the internal state of atoms [32] and cavity-QED test [33].

3.2 Bayesian quantum feedback

Markovian quantum feedback uses each instant measurement signal to control the Hamiltonian of a quantum system and doesn't use the previous knowledge about the system to be controlled. In fact, there are many other ways in which the measurement signal may be fed back to affect the system. Therefor Doherty and Jacobs presented a quantum feedback scheme using continuous state estimation in 1999, where they used certain integrals of the measurement records to provide specific information [21]. They made the best of the detailed information from measurement, and divided quantum feedback control process into two steps: a state estimation step and a feedback control step. Since the best state estimation will use all previous measurement results, not just the latest one, which is analogous to classical Bayesian estimation, the feedback is called Bayesian quantum feedback [21, 34, 35].

Recently, Doherty *et al.* also tried to consider separately optimizing state estimation step and feedback control step [36]. They considered optimizing desirable properties of each under the minimal constraint that the available strength of both is limited and identified an information tradeoff between information and disturbance in quantum feedback control. Wiseman *et al.* have done comparative research on Bayesian quantum feedback and Markovian quantum feedback, and the result has shown that Bayesian quantum feedback is never inferior, and is usually superior, to Markovian quantum feedback in stabilizing the quantum state of the simplest nonlinear quantum system [34].

Bayesian quantum feedback has been used to cool and confine a single quantum degree of freedom [21], switch the state of a particle in a double-well potential [35] and stabilize the internal state of atoms [34]. Besides, Korotkov *et al.* used it to control the decoherence of solid-state qubit [37, 38]. The scheme is shown as Fig. 1. The state of qubit is described by ρ and it interacts with environment. The current $I\,(t)$ from the detector is used to calculate $\rho\,(t)$ through evolution equation, then compare it with desired ρ and obtain the feedback signal. Hence one can produce suitable control to suppress qubit decoherence. The result showed that Bayesian quantum feedback can be used to control decoherence [37].

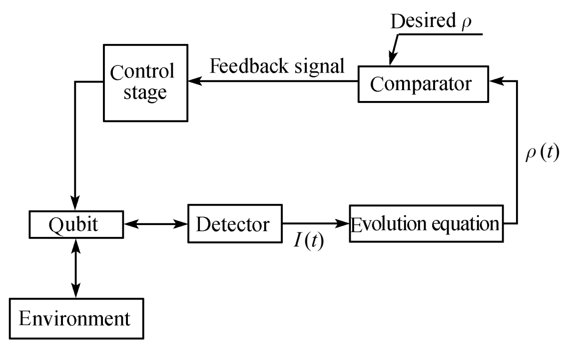

Fig. 1 Control of decoherence of solid-qubit using quantum feedback [37].

3.3 Non-Markovian quantum feedback with time delay

Both Markovian quantum feedback and Bayesian quantum feedback ignore the effect of feedback time delay, that is to say, we always assume the feedback delay $\tau \to 0$. As a result, the effect of feedback can be expressed in terms of an effective master equation and the problem is much easier to handle. The treatment is justified whenever the feedback delay time is much smaller than the system time scale. When we consider some stationary state phenomenon, the feedback delay time τ has to be compared with the cavity relaxation time γ^{-1} and for some sufficiently good systems the condition $\gamma\tau \ll 1$ is usually satisfied [22]. However, the delay can't be ignored in some situations. For example, when we use the quantum feedback for decoherence control, the delay τ and the decoherence time t_{dec} must be considered simultaneously. In many cases, the unavoidable nonzero feedback delay time may have important effects and it would be important to deal with the exact non-Markovian problem with $\tau \neq 0$ [22].

Giovannetti and co-workers first studied the non-Markovian quantum feedback with time delay in 1999 [22]. They completely solved the non-Markovian dynamics in the presence of a nonzero feedback delay by considering the time evolution of the probability distribution of the measured field quadrature and of the characteristic function. They also considered in particular the possibility of inhibiting the decoherence of a Schrödinger-cat state initially generated in the cavity and their results showed that feedback can also improve the dynamics of quantum systems for the delay time not too large [22]. In 2001, Wang *et al.* also gave a rigorous analysis of an anti-decoherence feedback scheme in a two-level atom with nonzero feedback time delay [39]. Using numerical simulations they found that the effect of nonzero time delay is qualitatively similar to the results obtained for no time delay but with inefficient detection and the time delay τ which is not too large is not fatal to decoherence control.

4 Coherent quantum feedback

Markovian quantum feedback, Bayesian quantum feedback and non-Markovian quantum feedback with time delay all use the feedback information from measurement results. According to the discussion of Section 2, we know that measurement destroys the quantum characteristics of feedback information, so feedback information becomes classical information. As a result, although the system under control is quantum system, feedback controller processes classical information and effective quantum channel in feedback loop isn't constructed, so the strategies can be called quantum control with classical feedback.

To remain the coherence in feedback loop, Lloyd proposed a coherent quantum feedback scheme in which the sensors, controller, and actuators all are quantum systems that interact coherently with the system to be controlled [23, 40]. In this feedback strategy, the controller gets, processes and feeds back quantum information, so the quantum characteristics in feedback loop have not been destroyed and the strategy can accomplish some tasks such as entanglement transfer that are not possible using classical feedback.

Consider the entanglement transfer in the case of spin system. The goal of the control process is to put the system spin in an entangled state [23]

$$\frac{1}{\sqrt{2}}|\uparrow\rangle|\uparrow\rangle_a + \frac{1}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle_a$$

where $|\uparrow\rangle_a$ and $|\downarrow\rangle_a$ are states of the "ancilla". If the direct interaction of the two spins is not allowed, they can not become entangled through the exchange of classical information alone. Hence quantum control with classical feedback can not accomplish the task. However, coherent quantum feedback can achieve the goal. First, prepare the ancilla spin in the state $(1/\sqrt{2})(|\uparrow\rangle_a + |\downarrow\rangle_a)$, then entangle the ancilla and controller spins by performing a CNOT on the controller spin with the ancilla spin as control. If the initial state of system spin is $(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)$, the state of the three spins is [23]:

$$(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)(1/\sqrt{2})(|\uparrow\rangle|\uparrow\rangle_a + |\downarrow\rangle|\downarrow\rangle_a) \tag{10}$$

Now perform the quantum feedback control and apply a third π pulse to flip the controller spin if and only if the system spin is in the state $|\uparrow\rangle$. As a result, the final state becomes [23]

$$(1/\sqrt{2})\left(|\uparrow\rangle|\uparrow\rangle'' + |\downarrow\rangle|\downarrow\rangle''\right)\left(\alpha|\uparrow\rangle' + \beta|\downarrow\rangle'\right) \tag{11}$$

Thus the coherent quantum feedback completes the goal of producing the desired entanglement between the system spin and the ancilla despite no direct interaction.

Moreover, since quantum control with classical feedback involves measurement, it is typically stochastic and destructive. However, coherent quantum feedback is deterministic and nondestructive [23].

5 Quantum feedback control based on cloning and recognition

Quantum feedback control with measurement has strong ability in information acquisition, but it destroys the coherence in feedback loop. On the contrary, coherent quantum feedback preserves the coherence of feedback loop, but its capability of information acquisition is limited. Therefor we consider a compromise between information acquisition and coherence maintenance [24, 41]. We separate quantum feedback control design into a state recognition step involving measurement and a feedback control step without measurement. This is obviously different from traditional quantum feedback since there the information acquisition necessarily results in destroying the state of quantum system. In the feedback scheme, quantum cloning and recognition are two important aspects, so we call it quantum feedback control based on cloning and recognition.

The general picture of quantum feedback control based on cloning and recognition is as follows (Fig. 2) [24]. The quantum system to be controlled is called controlled object. The actuator generates input signal to drive the object and its output is sent into an optimal cloning machine (quantum cloner). The quantum cloner clones the state, generates many copies. Recognizer receives N unknown copies, makes some measurements on them and obtains some information about their states. Then, one can recognize the N copies through appropriate recognition algorithm. If the N copies are "good" enough, the recognizer gives an "on" signal to the actuator, and the actuator receives another M copies from the quantum cloner as feedback and generates new quantum signal to drive the controlled object until the given control target is reached. If the N copies are not "good" enough, the recognizer will send an "off" signal to the actuator, and the actuator will not receive feedback information determined by feedback controller.

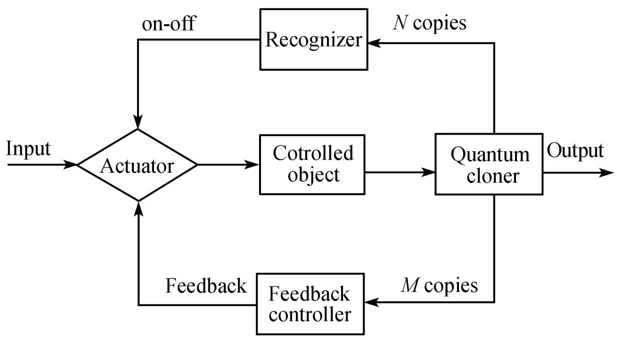

Fig. 2 Quantum feedback control based on cloning and recognition [24].

In the feedback control scheme, our objective is both to acquire information and not to destroy quantum information channel. Hence quantum cloning and feedback can not involve general quantum measurement. On the other hand, according to no-cloning theorem [42], arbitrary unknown quantum state cannot be copied exactly, and this is also an important limit on quantum control theory. However, this doesn't exclude the possibility of approximately or probabilistically cloning quantum state [43]. In fact, there are two kinds of quantum cloning machines: probabilistic cloning machine [44] and optimal universal quantum cloning machine [45, 46]. Probabilistic cloning machine is only suitable for linearly independent quantum states, where the machine yields faithful copies of the input state with a postselection of the measurement result [44]. However, optimal universal quantum cloning machine can approximately copy arbitrary unknown quantum state with unity probability [45]. It can be decomposed into rotations and CNOT gates and doesn't involve measurement. Hence we use approximate cloning to amplitude the output state of the object, that is to say, the output state is approximately copied, some copies are used to obtain information through quantum measurement and other copies are used to determine feedback.

The $1 \to 2$ cloning process can be described by the transformation:

$$|s\rangle_a |M\rangle_x \to |s\rangle_a |s\rangle_b |\tilde{M}\rangle_x \tag{12}$$

where $|s\rangle_a$ is the state of the original mode, $|s\rangle_b$ is the copied state, $|M\rangle_x$ is the original state of the cloning machine and $|\tilde{M}\rangle_x$ is the final state of the cloning machine. The whole process of quantum cloning is to produce at the output of the cloning machine two identical states $|s\rangle_a$ and $|s\rangle_b$. Considering $1 \to M{+}N{+}1$ cloning process, it can be described as follows:

$$|s\rangle_a |M\rangle_x \to |s\rangle_a |s\rangle_b \cdots |s\rangle_{M+N+1} |\tilde{M}\rangle_x \tag{13}$$

The quantum cloner generates $(M+N+1)$ copies and sends N copies into the state recognizer. Since these copies are approximate, we must recognize them using suitable recognition method [47, 48]. For generalization, represent these copies with density matrices $\{\rho_1, \rho_2, \cdots, \rho_N, \rho_{N+1}, \cdots, \rho_{N+M+1}\}$. Assume the unknown copies that the recognizer receive are $U_R = \{\rho_1, \rho_2, \cdots, \rho_N\}$. We can acquire part information and determine parameters of $\rho_i (1 \leqslant i \leqslant N)$ through suitable measurement. To recognize the copies, we should create a "objective state" ρ_o. For example, the simplest method is equal weight average:

$$\rho_o = \frac{1}{N}\sum_{i=1}^{N}\rho_i \tag{14}$$

Look upon ρ_o as "objective state", one can calculate the trace distance $D(\rho_i, \rho_o)$ between ρ_i and ρ_o [6, 49]:

$$D(\rho_i, \rho_o) \equiv \frac{1}{2}\mathrm{Tr}\,|\rho_i - \rho_o| \tag{15}$$

Compare them with the beforehand given trace distance threshold D_0. If all trace distances satisfy $D(\rho_i, \rho_o) \leqslant D_0$, recognize them as a class, the state recognizer generates an "on" signal, and the actuator receives another M copies from the cloner as feedback. According to the feedback information, the actuator generates new quantum signal to drive the controlled object. Otherwise, the state recognizer will send an "off" signal to the actuator, and the actuator will not receive feedback copies from the quantum cloner [24].

In this feedback scheme, the design of quantum feedback algorithms is separated into two steps: a state recognition step and a feedback control step. The aim of state recognition step is to obtain information and the process involves quantum measurement, so it is destructive. However, the feedback process doesn't necessarily acquire information and doesn't involve measurement, so it can preserve quantum coherence [24]. In fact, we give a compromise between information acquisition and measurement disturbance in view of the characteristics of quantum measurement. The compromise is realized through approximate cloning and renouncing precise feedback. The relations between different quantum feedback control schemes can be shown as Fig. 3.

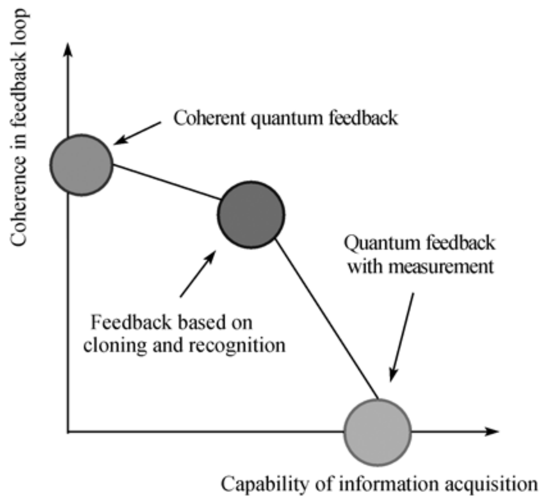

Fig. 3 Relations between different quantum feedback control schemes.

6 Concluding remark

Feedback control of quantum system is a rapidly developing research field [50－56]. In this paper, we have discussed several kinds of quantum feedback control schemes including Markovian quantum feedback, Bayesian quantum feedback, non-Markovian quantum feedback with time delay, coherent quantum feedback, and quantum feedback control based on cloning and recognition. These feedback schemes have different advantages. For example, the experiment realization is easiest for Markovian quantum feedback and the ability of coherence maintenance of coherent quantum feedback is the best.

In practical applications, the most important aspects for quantum feedback are information acquisition and coherence maintenance. Quantum feedback control based on cloning and recognition achieves a compromise between them. With the rapid development of quantum information technology, it is possible to use some other information technology approaches to design quantum feedback scheme. Simultaneously, all kinds of quantum feedback strategies can also be applied to large-scale quantum computation, practical quantum communication, quantum robot [57] and quantum intelligence [58－60].

Acknowledgements This work was supported in part by the National Natural Science Foundation of China (No. 60575033), the Innovation Research Project of Science and Society Practice of the Chinese Academy of Science for Graduate Students (No. 2004-18), and the Innovation Fund of the University of Science and Technology of China for Graduate Students (No. KD2004048).

References

1. Shapiro M. and Brumer P., Principles of the quantum control of molecular processes. New Jersey: John Wiley & Sons, Inc., 2003
2. Rabitz H., de Vivie-Riedle R, Motzkus M, et al.,Whither the future of controlling quantum phenomena? Science, 2000, 288: 824－828
3. Dong Dao-yi and Chen Zong-hai, Applications of quantum control theory in chemistry. Progress in Chemistry, 2005, 17 (4): 581－587 (in Chinese)
4. Chen Zong-hai, Dong Dao-yi, and Zhang Chen-bin, Quantum control: An introduction. Hefei: University of Science and Technology of China Press, 2005
5. Rice S. and Zhao M., Optical Control of Molecular Dynamics. New York: Wiley, 2000
6. Nielsen M. A. and Chuang I. L., Quantum computation and quantum information, Cambridge: Cambridge University Press, 2000
7. Solomon A. I. and Schrirmer S. G., Limitations in quantum control, Int. J. Mod. Phys. B, 2002, 16: 2107－2112
8. Huang G. M., Tarn T. J., and Clark J. W., On the controllability of quantum-mechanical systems. J. Math. Phys., 1983, 24 (11): 2608－2618
9. Albertini F. and D'Alessandro D., Notions of controllability for bilinear multilevel quantum systems, IEEE Trans. Automat. Contr., 2003, 48 (8): 1399－1403
10. Schirmer S. G., Fu H, and Solomon A. I., Complete controllability of quantum systems, Phys. Rev. A, 2001, 63: 063410
11. Zhang Chen-bin, Dong Dao-yi, and Chen Zong-hai, Control of non-controllable quantum system: A quantum control algorithm based on Grover iteration, J. Opt. B: Quantum Semiclass Opt., 2005, 7: S313－S317
12. Peirce A. P., Dahleh M., and Rabitz H., Optimal control of quantum-mechanical systems: Existence, numerical approximation, and applications, Phys. Rev. A, 1988, 37 (12): 4950－4964
13. Rabitz H., Optimal control of quantum systems: Origins of inherent robustness to control field fluctuations, Phys. Rev. A, 2002, 66: 063405
14. Khaneja N., Brockett R., and Glaser S. J., Time optimal control in spin systems, Phys. Rev. A, 2001, 63: 032308
15. Warren W. S., Rabitz H., and Dahleh M., Coherent control of quantum dynamics: the dream is alive, Science, 1993, 259: 1581－1589
16. Weinacht T. C. and Bucksbaum P. H., Using feedback for coherent control of quantum systems, J. Opt. B: Quantum Semiclass Opt., 2002, 4: R35－R52
17. Rice S. A., Interfering for the good of a chemical reaction, Nature, 2001, 409: 422－426
18. Dong Dao-yi and Chen Zong-hai, Progress of the research on quantum feedback control, Chinese Journal of Quantum Electronics, 2005, 22 (6): 833－839 (in Chinese)
19. Haus H. A. and Yamamoto Y., Theory of feedback-generated states, Phys. Rev. A, 1986, 34 (1): 270－292
20. Wiseman H. M. and Milburn G. J., Quantum theory of optical feedback via homodyne detection, Phys. Rev. Lett., 1993, 70 (5): 548－551
21. Doherty A. C. and Jacobs K., Feedback control of quantum systems using continuous state estimation, Phys. Rev. A, 1999, 60: 2700－2711
22. Giovannetti V., Tombesi P., and Vitali D., Non-Markovian quantum

feedback from homodyne measurements: The effect of a nonzero feedback delay time, Phys. Rev. A, 1999, 60 (2): 1549－1561
23. Lloyd S., Coherent Quantum Feedback, Phys. Rev. A, 2000, 62: 022108
24. Dong Dao-yi, Zhang Chen-bin, Chen Zong-hai, and Chen Chun-lin, Information-technology approach to quantum feedback control, Int. J. Mod. Phys. B, 2006, 20: 1304－1316
25. Yamamoto Y., Imoto N., and Machida S., Amplitude squeezing in a semiconductor laser using quantum nondemolition measurements and negative feedback, Phys. Rev. A, 1986, 33 (5): 3243－3261
26. Dong Dao-yi, Chen Chun-lin, Chen Zong-hai, and Zhang Chen-bin, Estimation-based information acquisition in quantum feedback control. ICCSA06, 2006, Dynamics of Continuous, Discrete and Impulsive Systems (in press)
27. Preskill J., Lecture Notes for Physics229: Quantum Information and Computation. California Institute of Technology, 1998. (http://www.theory.caltech.edu/people/preskill/ph229/)
28. Braginsky V. B. and Khalili F. Y., Quantum nondemolition measurements: the route from toys to tools, Rev. Mod. Phys., 1996, 68: 1－11
29. Braginsky V. B., Vorontsov Y. I., and Thorne K. S., Quantum nondemolition measurements, Science, 1980, 209: 547－557
30. Tombesi P. and Vitali D., Physical realization of an environment with squeezed quantum fluctuations via quantum-nondemolition-mediated feedback and Phys. Rev. A, 1994, 50 (5): 4253－4257
31. Wiseman H. M. and Milburn G. J., Squeezing via feedback, Phys. Rev. A, 1994, 49 (2): 1350－1366
32. Wang J. and Wiseman H. M., Feedback-stabilization of an arbitrary pure state of a two-level atom, Phys. Rev. A, 2001, 64: 063810
33. Reiner J. E., Wiseman H. M., and Mabuchi H., Quantum jumps between dressed states: A proposed cavity-QED test using feedback, Phys. Rev. A, 2003, 67: 042106
34. Wiseman H. M., Mancini S., and Wang J., Bayesian feedback versus Markovian feedback in a two-level atom, Phys. Rev. A, 2002, 66: 013807
35. Doherty A. C., Habib S., Jacobs K., et al., Quantum feedback control and classical control theory, Phys. Rev. A, 2000, 62: 012105
36. Doherty A. C., Habib S., and Jungman G., Information, Disturbance, and Hamiltonian Quantum Feedback Control, Phys. Rev. A, 2001, 63: 062306
37. Korotkov A. N., Selective quantum evolution of a qubit state due to continuous measurement, Phys. Rev. B, 2001, 63: 115403
38. Ruskov R. and Korotkov A. N., Quantum feedback control of a solid-state qubit. Phys. Rev. B, 2002, 66: 041401R
39. Wang J., Wiseman H. M. and Milburn G. J., Non-Markovian homodyne-mediated feedback on a two-level atom: a quantum trajectory treatment, Chem. Phys., 2001, 268: 221－235
40. Nelson R. J., Weinstein Y., Cory D., et al., Experimental demonstration of fully coherent quantum feedback, Phys. Rev. Lett., 2000, 85: 3045－3048
41. Dong Dao-yi, Zhang Chen-bin, and Chen Zong-hai, Quantum feedback control using quantum cloning and state recognition, In: Proceedings of the 16th IFAC World Congress, Prague, 2005, July 4－8: 1965
42. Wootters W. K. and Zurek W. H., A single quantum cannot be cloned. Nature, 1982, 299: 802－803
43. Scarani V., Iblisdir S., Gisin N., et al., Quantum cloning, Rev. Mod. Phys., 2005, 77 (4): 1225－1256
44. Duan L. M. and Guo G. C., Probabilistic cloning and identification of linearly independent quantum states, Phys. Rev. Lett., 1998, 80 (22): 4999－5002
45. Bužek V. and Hillery M., Quantum copying: Beyond the no-cloning theorem, Phys. Rev. A, 1996, 54 (3): 1844－1852
46. Gisin N. and Massar S., Optimal quantum cloning machines, Phys. Rev. Lett., 1997, 79 (11): 2153－2156
47. Dong Dao-yi, Chen Zong-hai, and Jiang Sheng-xiang, Pattern recognition of quantum information based on pattern-distance, Journal of Systems Engineering and Electronics, 2005, 16 (4): 917－923
48. Dong Dao-yi and Chen Zong-hai, Clustering recognition of quantum states based on quantum module distance, Acta Sinica Quantum Optica, 2003, 9:144－148
49. Fuchs C. A. and van de Graaf J., Cryptographic distinguishability measures for quantum-mechanical states, IEEE Trans, Information Theory, 1999, 45 (4): 1216－1227
50. Jacobs K., How to project qubits faster using quantum feedback, Phys. Rev. A, 2003, 67: 030301R
51. Handel R. van, Stockton J. K., and Mabuchi H., Feedback control of quantum state reduction, IEEE Trans. Automat. Contr., 2005, 50: 768－780
52. Morrow N. V., Dutta S. K., and Raithel G., Feedback control of atomic motion in an optical lattice, Phys. Rev. Lett., 2002, 88: 093303
53. Handel R. van, Stockton J. K., and Mabuchi H., Modelling and feedback control design for quantum state preparation, J. Opt. B: Quantum Semiclass Opt., 2005, 7: S179－S197
54. Geremia J. M., Stockton J. K., and Mabuchi H., Real-time quantum feedback control of atomic spin-squeezing, Science, 2004, 304 (5668): 270－273
55. Gough J., Belavkin V. P., and Smolyanov O. G., Hamilton-Jacobi-Bellman equations for quantum optimal feedback control, J. Opt. B: Quantum Semiclass Opt., 2005, **7:** S237－S244
56. Combes J. and Jacobs K., Rapid state reduction of quantum systems using feedback control, Phys. Rev. Lett., 2006, 96: 010504
57. Dong Dao-yi, Chen Chun-lin, Zhang Chen-bin, and Chen Zong-hai. Quantum robot: structure, algorithms and applications, Robotica, in press (DOI: 10.1017/S0263574705002596)
58. Dong Dao-yi, Chen Chun-lin, Chen Zong-hai, and Zhang Chen-bin, Quantum mechanics helps in learning for more intelligent robots, Chin. Phys. Lett., 2006, 23 (7): 1691－1694
59. Dong Dao-yi, Chen Chun-lin, and Chen Zong-hai, Quantum reinforcement learning, ICNC2005, Lecture Notes in Computer Science, 2005, 3611: 686－689
60. Dong Dao-yi, Chen Chun-lin, Zhang Chen-bin, and Chen Zong-hai, An autonomous mobile robot based on quantum algorithm, CIS05, Lecture Notes in Artificial Intelligence, 2005, 3801: 393－398