Monitoring particle trajectories for wave function parameter acquisition in quantum edge computation

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1. Introduction

Tasks programmed based on a well-established algorithm, including probabilistic ones [1], are performed by robots in the exact way. With the aim of moving such robots as autonomously as possible, research on AI [2] that should be mounted on robots has made remarkable progress. By combining high-precision sensors, it is expected that AI-equipped robots perform even higher quality tasks. Connection with the IoT (Internet of Things) [3] also raises such expectations. Further in order to control such AI-equipped robots online, a computer that processes high loads at high speed is required. The possibilities of online processing by sensor fusion will be expanded if quantum computers, which are currently making great progress [4, 5] as high-load and high-speed ones, are used. It is desirable that such a high-speed computer be the "edge" of a robot in order to combine it with sensor information. That is, what we require is a quantum computer that can withstand a high load. If so, it is natural to consider introducing quantum computing into AI in robot. By the way, even if our robot with AI of high precision computer looks autonomous, the performance results are what designers require. Robots may also fall in love, hate, doubt for no reason, or emotionally dare do something they know obviously bad – within the designer's frame. We think this kind of emotion cannot be expressed by the accumulation of ordinary logic(-circuits). There have been many studies to artificially create consciousness. Among them the works that is based on the neural network structure [6] and that applies symbol emergence [7] are very intriguing. We focus on these various attempts, which are based on quantum mechanics [8, 9]. One of the reasons is, of course, the remarkable progress of quantum computer research. Above all, we have an argument [10]. Nonalgorithmic nature of probabilistic prediction in quantum phenomena is possibly an essential ingredient that underlies mind or consciousness. This argument is the other but rather more important reason for us to take quantum computing as robots AI.

So what is quantum computing like? Quantum computer is a high-speed computing device that makes full use of quantum mechanical superposition, that is, quantum parallelism. Let two orthogonal unit vectors \( |0\rangle \) and \( |1\rangle \) represent two energy levels in a physical system. A basic element of a quantum computer is "qubit", a linear combination with complex coefficients \( \alpha \) and \( \beta \) satisfying \( |\alpha|^2 + |\beta|^2 = 1 \),

\[ \psi = \alpha |0\rangle + \beta |1\rangle. \] (1)

That is, \( n \) qubits represent exponentially large numbers of \( 2^n \) binary quantities at once. Moreover, the operations between these \( 2^n \) binary data are performed simultaneously. For this reason, a dramatic improvement, quadratic or even exponential speedup,
in calculation can be expected. However, even if the calculations are performed in parallel, only one result can be retrieved. Therefore, just the parallelism does not necessarily mean increase in the calculation speed. Even so, quantum calculations cannot be performed unless time evolves in the superposition state. Attempts are being made every day to take advantage of quantum computing [11]. Another recent topic that should not be forgotten is Google’s achievements. Google [12] claims that 200[s] is enough for a quantum processor with only 53 qubits, $\sim 10^{16}$ binary data, to perform a calculation that would take 10,000 years in the conventional supercomputer. This is an unfair result of problems that classical computers are not good at. However, the effectiveness of using quantum mechanics has certainly been shown. But it’s very difficult to maintain that superposition state. This is because the level of energy that distinguishes each state is very small when viewed from the macro and sometimes mixes up. Micro world is governed by Dirac constant $\hbar = 1.05 \times 10^{-34}$[Js]. A one-dimensional quantum dot with a depth $V_0$ and a width $2 \times S$ gives a particle with mass $m$ two energy levels, if $\frac{\hbar^2}{2mS^2} \left( \frac{S}{2} \right)^2 < V_0 \leq \frac{\hbar^2}{2mS^2} \pi^2$ holds. Very small thermal noise $\sim 20$[mK] can mix up energy levels in a quantum dot with its width $S \sim 10$[nm], when we take $m \sim 10^{-27}$[kg] (hydrogen atom mass as a typical quantum element). On the other hand, the progress of the calculation takes much longer, $\sim 10^3 \sim 10^4$ times longer, than the time typical in the atomic world. In order to keep the superposition at the relatively long time intervals, special equipment is required to shut off the quantum computing system from the outside thermal noise. Such equipment is usually very large, and cryogenic temperatures are often used. The robot that works in room temperature would have to be put in a cryogen to maintain linear quantum superposition. Although the context is different, the example of nuclear power generation shows difficulties for macro humans to control the micro world.

What about making only the way of solving problems quantum mechanical? This corresponds to an idea to use quantum computing as one of various programs of calculation on the current classical computer. We also see the literature [13] that discusses the proper use of algorithm quantum/classical and computer quantum/classical. Especially in the AI field, there are many ideas to use quantum concept on a classical computer to improve the efficiency of calculation. This method certainly outperforms the conventional method. Quantum neural nets, quantum machine learning [14] and quantum Boltzmann machine [15] are already well known in engineering society. Our works on quantum neural nets [16–18] revealed that quantum principles – superposition, probability interpretation, entanglement have guaranteed the high processing capacity. But the quantum simulator uses so-called “projection postulate” where probabilities are assigned according to the superposition coefficient. It is certainly difficult for the fixed calculation method to explain indescribable feelings such as emotions and good and evil.

In the end, what we want to explore in this paper is to implement quantum properties in hardware rather than as an algorithm in a macro robot’s edge without using a big device. For this, we propose a method to carry out quantum computation only with classical mechanical devices, not on a large scale. The purpose of the quantum computation is to equip the robot with “consciousness” that cannot be exhausted by logic circuits alone. This paper is closely related to [19, 20], where we also have examined mechanical apparatus design using omni-directional mobile robot approximated as a point particle without any internal structure. Parameter calculation [19] to design qubit and some calculations [20] on quantum gate have been done. The result [19] of tunnelling phenomena is rearranged in this paper. The ‘particles’ referred to below include not only physical mass points but also omni-mobile robots that are treated as point particles without any internal structure in the present approximation.

In Section 2, we examine possibility of macroscopically constructing superposition that needs to be maintained. Subsequently, an attempt to create fluctuation to give systems quantum nature is shown in Section 3. We take Deutsch’s problem in Section 4 to show role of the fluctuation in quantum computation. Section 5 gives a simple configuration of an actual qubit. Conclusion is given in Section 6 with some discussion. Numerical values are to be read in [MKS] unit.

### 2. Superposition in quantum computation

Take a problem to sum up two one-digit binary numbers to result in another one-digit binary number $S$ and carry flag $C$. In quantum computing systems we set an initial state, $\psi(0)$, as a product of linear combinations, $\psi(0) = (\alpha_1 |0\rangle + \beta_1 |1\rangle) \otimes (\alpha_2 |0\rangle + \beta_2 |1\rangle)$. The state $\psi$ develops in time according to Schrödinger equation under a Hamiltonian that drives the system. Let the Hamiltonian depend on parameters $\gamma$ and a function $\phi_{SC}$ be a state that represents the specific values $S$ and $C$. Our state maintains a linear combination $\psi(t; \gamma) = \sum_{SC} a_{SC}(t; \gamma) \phi_{SC}$ of possible SCs. An elapsed time $T$ is taken appropriately to result in one required output, e.g. $1 + 1 = (S = 0, C = 1)$, by a measurement at $T$ in a maximum probability. We need a calculation program where this maximum probability $|a_{SC}(T; \gamma)|^2$ is as close to 1 as possible. Let us change the way of thinking here. If the parameter values $\gamma$ are known, we also know when this probability $|a_{SC}(T; \gamma)|^2$ has the maximum. In other words, we also know when $\psi(t; \gamma)$ reduces to $\phi_{SC}$ with the maximum probability. Is this the same as measuring $SC$? So how can we know the parameter values? If a particle described by the wave function $\psi(t; \gamma)$ could exist, the particle motion is given by a...
formula dependent on the parameter, \( x = x(t; \gamma) \). The parameters \( \gamma \) could be determined by monitoring the particle trajectory. Of course, even in this case, the device must be sufficiently cooled. But if we can simulate quantum fluctuations with macroscopic devices, monitoring the particle trajectory is possible to determine the parameters of the superposed states. We do not need any large and expensive equipment. However, superposition presupposes that matter exists in the form of waves. We only have Newtonian particles in our macroscopic world. Waves are all composed of particles. So, let us consider whether there is a theory that could be used in macro worlds as well. Born’s probability interpretation [21] gives standard way of practical calculation. A complex wave \( \psi \) governed by Schrödinger equation gives probabilities of eigen states. A particle appears with probability given by squared absolute value \( |\psi|^2 \) of the wave function. However, the standard theory cannot explain the necessity of realizing the certain eigen state. Various theorists [22–24] have tried to consistently understand the problem [20]. Among them the hidden variable theory [22] is the classical mechanical and causal reconstruction of quantum mechanics by Bohm. We have only particles. The particle moves under classical potential force and quantum fluctuation. The wave has a role to generate the wave function. If we can generate fluctuations, we can use causal reconstruction. But the following questions arise. Wasn’t the quantum effect negligible in the macro world? Wasn’t a huge number of trials necessary to be consistent with the probability interpretation? Furthermore, we still don’t know how to implement. The first and the second are answered positively in Sections 3 and 4, respectively. We discuss in the last of Section 4 on the third question.

3. Creating quantum effects in macroscopic world

We start with preparing a new constant \( H_R \) of physical dimension of action([Js]) instead of \( \hbar \). Schrödinger equation characterized by the new constant \( H_R \) is written down. Causal formulation with changing the physical constant \( \hbar \) to \( H_R \) is positioned as optimal feedback control convenient for numerical calculation. Such a view does not exist to our knowledge [25]. Feedback is also indispensable when actually moving the omnidirectional robot.

Take a constant \( H_R \) that plays a role of \( \hbar \) according to the strategy explained above. Schrödinger equation for a particle with mass \( m \) moving in one-dimensional coordinate \( x \) under a potential \( V(x; t) \) is given as

\[
iH_R \frac{\partial \psi(x; t)}{\partial t} = \left( -\frac{H_R^2}{2m} \frac{\partial^2}{\partial x^2} + V(x; t) \right) \psi(x; t).
\]

(2)

Substitute into (2) a polar coordinate representation

\[
\psi(x; t) = R(x; t) e^{i \frac{S(x; t)}{H_R}}.
\]

(3)

With the definition

\[
V^q(x; t) \equiv -\frac{H_R^2}{2m} \frac{\partial^2 R(x; t)}{\partial x^2} \frac{1}{R(x; t)},
\]

(4)

the real part of the equation after multiplying \( e^{-i \frac{S}{H_R}} \) gives us a generalized formula of Hamilton–Jacobi equation

\[
-\frac{\partial S(x; t)}{\partial t} = \frac{1}{2m} \left( \frac{\partial S(x; t)}{\partial x} \right)^2 + V(x; t) + V^q(x; t).
\]

(5)

For mechanical systems, the behaviour is usually controlled by manipulating force. However, in a robot designed to move freely in all directions, sometime the velocity demand is useful [26]. So we regard the velocity \( u \equiv \dot{x} \) as control variable in the state equation

\[
\dot{x} = u.
\]

(6)

At this time, (5) tells that our system described by (2) is an optimal feedback control system under the penalty function

\[
L(x; u; t) = \frac{m}{2} u^2 - \left( V(x; t) + V^q(x; t) \right).
\]

(7)

According to the standard textbook [27] on control theory, we explicitly calculate optimal feedback as

\[
u = \frac{1}{m} \frac{\partial S(x; t)}{\partial x} = \frac{H_R}{m} \psi^*(x; t) \frac{\partial \psi(x; t)}{\partial x} - \psi(x; t) \frac{\partial \psi^*(x; t)}{\partial x},
\]

(8)

where (3) gives our formula in terms of \( \psi \) in the second line. According to the formulae (5), (6), (7), (8), it is obvious [22] that quantum mechanics is a classical causal mechanics under the deterministic fluctuation \( V^q \), (4). A would-be divergence due to zero points of \( R(x; t) \) is avoided [28]. Due to (4) Newton motion equation \( m\ddot{x} = -\frac{\partial}{\partial x} (V(x) + V^q(x; t)) \) requires third-order differentiation \( \frac{\partial^3}{\partial x^3} \). Our optimal feedback formulation, (6) and (8), that requires only first-order differentiation is obviously better in calculation in design stage than that based on Newton equation. To deal with possible friction, quantum mechanics must be extended to dissipative systems. A special form of friction, \( \tilde{F}_{fric} = -\gamma \dot{x} \) can be quantized by usual canonical formulation [29].

Our classical mechanics governed by the Hamilton–Jacobi equation (5) can explain a typical quantum phenomenon, barrier penetration [19]. A wave packet located initially at minus infinity, \( x_c = -\infty \), moves in...
the plus direction with a momentum $p$. The wave collides with the barrier of height $V_b$ centred at $x = x_b$ with a thickness $b$. Even if the kinetic energy $K = \frac{p^2}{2m}$ is less than the barrier height $V_b$, the fluctuation force makes some quantum particles jump over the wall. Particles that start with their various initial positions independently move according to the feedback law (8). After sufficient elapsed time, we count how many particles jump over the barrier. If $N_N$ particles out of the prepared $N$ jump over the barrier, the ratio $\frac{N_N}{N}$ gives the tunnel probability. Take a system with $N$ particles out of the prepared $N$ jump over the barrier, the ratio $\frac{N_N}{N}$ gives the tunnel probability. Take a system with $N$ particles out of the prepared $N$ jump over the barrier, the ratio $\frac{N_N}{N}$ gives the tunnel probability. Take a system with $N$ particles out of the prepared $N$ jump over the barrier, the ratio $\frac{N_N}{N}$ gives the tunnel probability.

| 0.2 | 0.1 | not penetrated | penetrated |
|------|------|----------------|------------|
| x[m] |       |                |            |
| -2   | -1   |                |            |
| 0    | 1    |                |            |
| 2    | 3    |                |            |
| Barrier region | 1 | 2 | 3 |

Figure 1. Tunnelling the barrier potential.

Determination of the authenticity of coins. Following that, intuitive interpretation of the algorithm based on quantum fluctuation is given.

Focusing on the coin design, if the front and back are the same, it is judged as a false coin, and if different, it is judged as a true coin. Take 0 and 1 represent the front and the back, respectively. If the corresponding design is expressed by a function $f(x)$, a task to be calculated is given as follows.

“For a function $f: \{0, 1\} \rightarrow \{0, 1\}$, determine if it satisfies $f(0) = f(1)$ or $f(0) \neq f(1)$, in as few times as possible.”

Deutsch built the circuit. The states $|0\rangle$ and $|1\rangle$ develop in time under a specified perturbation to generate $|x\rangle = H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|y\rangle = H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$, respectively. Our function $f$ gives a logical “exclusive or” $\oplus$.

$$|\Psi_{out}\rangle = U_f(|x\rangle |y\rangle) = |x\rangle |y \oplus f(x)\rangle$$ (9)

on the tensor product. This $U_f$ is also the result of time evolution under appropriate physical interaction. Note that $|0\oplus f(x)\rangle = |f(x)\rangle$ and $|1\oplus f(x)\rangle = \overline{|f(x)\rangle}$. Linearity of $U_f$ helps us to define $|\Psi_{out}\rangle \equiv |f(0)\rangle - |f(1)\rangle$ and calculate the output result as

$$U_f(|x\rangle |y\rangle) = \frac{|0\rangle + |1\rangle}{\sqrt{2}} |\Psi_{out}\rangle, \quad f(0) = f(1), \quad (10)$$

$$U_f(|x\rangle |y\rangle) = \frac{|0\rangle - |1\rangle}{\sqrt{2}} |\Psi_{out}\rangle, \quad f(0) \neq f(1). \quad (11)$$

Equations (10) and (11) mean that

- in case the first qubit of the output $|\phi^+\rangle \equiv \frac{|0\rangle + |1\rangle}{\sqrt{2}}$, we know $f(0) = f(1)$,
- in case $|\phi^-\rangle \equiv \frac{|0\rangle - |1\rangle}{\sqrt{2}}$, we know $f(0) \neq f(1)$.

However, it is not possible to distinguish between $|\phi^+\rangle$ and $|\phi^-\rangle$. In both these superposition states, we measure the eigen state $|0\rangle$ or $|1\rangle$ in the equal probability. Judging the authenticity is completed only after the Hadamard transformation $H$:

- case $|0\rangle$: $f(0) = f(1)$,
- case $|1\rangle$: $f(0) \neq f(1)$.

However, the trajectories of particles surfing on the waves are different between states $|\phi^+\rangle$ and $|\phi^-\rangle$. That is, if the behaviour of the particles is monitored, no extra $H$ transformation is necessary.

The causal formulation of quantum mechanics can give an intuitive explanation of Deutsch’s problem. It is necessary to turn the coin over once and check the pattern to see if the coin is genuine. However, if the coins are falling while rotating, you can see the pattern at the same time and judge the authenticity at once. But how do you “see”? Assume that the strength and

4. Role of fluctuation in quantum algorithm

Deutsch [4] first embodied an idea of computing method based on quantum mechanical “superposition principle.” A problem to be solved is explained as
direction of the “wind” around the falling coin will be different when the coin is genuine and when it is fake. If there is a particle that moves by the wind, the particle certainly feels the wind or sees whether the coin is genuine or fake. Between the state $|\phi^+\rangle$ (fake coin) and $|\phi^-\rangle$ (genuine), the quantum fluctuations, the direction and strength of the wind, are different. Even if the H transformation in the last step to distinguish between $|\phi^+\rangle$ and $|\phi^-\rangle$ is not performed, the authenticity can be judged only by the difference between these states. At this point, we can answer the second question: wasn’t being, we will use self-driven omni-mobile robots [19, 20]. Although we use classical computer simulations in the latter case, our method has great advantages. Due to the existence of friction noise, the results cannot be completely predicted. Here, emergence of human consciousness, which is characterized by things that cannot be expressed only by fixed algorithms, is expected.

5. Determining wave function parameters

As given in (1), a basic element of a quantum computer, qubit, is a linear combination of two unit vectors. We actually configure the qubit system. It means designing a quantum mechanical system with two energy eigenstates. Monitoring particle motion in the system gives wave function parameters.

We take a particle that moves freely on a one-dimensional straight line. Let the particle be confined in a region $x \in [-S, S]$ between two walls with its height $V_0$. Four system parameters $m, V_0, S$ and $H_R$ are determined from a comprehensive and bird’s-eye view of the following: two energy levels, required values of clock and power consumption values, and macroscopic character. Here, under a macroscopic structure assumed in advance, parameters that satisfy the two levels condition are taken. The clock and power consumption are checked ex post facto based on the obtained results.

Note that our design parameter $H_R$ is chosen freely, while in quantum mechanics, $H_R \equiv \hbar$ is a physical constant. A nondimensional constant $B^2 \equiv \frac{2mV_0S^2}{\hbar^2}$ must be taken as $\frac{\pi}{2} < B \leq \pi$ to give two levels of energy eigenstates. Under given $m$ and $S$, the two inequalities tell how to generate a qubit by taking $H_R$ when $V_0$ is set.

![Figure 2. Design constant $H_R$, frequency $f$ and power $P$ calculated under given quantum dot height $V_0$ for $m = 5 = 1$.](image)

For example, let us simply take unit values in MKS, $m = S = 1$. Figure 2(a) shows a narrow area between the dotted blue line ($B = \frac{\pi}{2}$) and the solid green line ($B = \pi$) in which the constant $H_R$ must come [19]. For clock $f$ and power consumption $P$, dimensional analysis helps us to estimate $f = \frac{V_0}{\pi H_R}$ [Hz] and $P = \frac{B^2}{S} V_0$ [W]. The solid red line and the dotted red line in (a) correspond to $f = 1$ Hz and 1 GHz, respectively. On the other hand, in (b), $P$ is given by the function of $V_0$, and two $f$-values are also shown here. For each $f$, $P$ takes the value of the narrow area between the blue dotted line and the green solid line. As shown by the V-mark a combination $V_0 = 1$, $H_R = 0.5$ can generate a qubit. For this choice, Figure 2 predicts $f \sim 1$ Hz and $P \sim 0.1 \sim 1$ W, low power consumption but very slow quantum computer. Downsizing the device to $m \sim 10$ pg, $S \sim 10$ μm allows a combination $f \sim 1$ GHz, $P \sim 1$ kW. If such a device is connected by 53-qubits, we obtain a supercomputer with very low power. What about the relationship with the human brain that operates at $\sim 50$ Hz under $\sim 20$ W? Suppose a metal particle or omni-mobile robot with $\sim 1$ mm radius and mass $m \sim 30$ mg moving in a dot with $S \sim 1$ cm is available. We can calculate that 53-qubits achieve $f \sim 1$ kHz with $P \sim 5$ W. From the results, applying our quantum computing device as a humanoid robot AI is possible.

Return to proceeding with the one qubit calculation under the condition $m = S = V_0 = 1$, $H_R = 0.5$. In Figure 3, we show the profiles of the potential $V(x)$, and the eigen functions $\phi_E(x)$ ($E$:even parity) and $\phi_O(x)$ ($O$:odd parity) corresponding to eigen energies $E_E = 0.17$ and $E_O = 0.63$, respectively. The state $\phi_E$ with lower eigen energy $E_E$ corresponds to $|0\rangle$, while $\phi_O$ to $|1\rangle$ with $E_O$. Take two complex numbers $c_E, c_O$ satisfying $|c_E|^2 + |c_O|^2 = 1$. We obtain the explicit form of the wave function

$$\psi(x; t) = c_E e^{i E_E t} \phi_E(x) + c_O e^{i E_O t} \phi_O(x).$$

(12)

Our quantum particle moving under optimal state feedback (8) takes a trajectory

$$x = x(t; c_E, c_O)$$

(13)

that depends on the weight $(c_E, c_O)$ of the two eigen functions in the wave function. We can determine the combination $(c_E, c_O)$ by measuring the trajectory of the quantum particle. In Figure 4, the trajectory denoted
as $\phi^\pm$ is the one (13) with $c_E = \pm c_O = \frac{1}{\sqrt{2}}$. When we measure that the particle moves as the red, $\phi^+$ line or blue, $\phi^-$ line, we determine the combination ($c_E$, $c_O$) as $(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$ or $(\frac{1}{\sqrt{2}}, -\frac{1}{\sqrt{2}})$. It means that monitoring the trajectory of the particle determines the output result, (10) or (11), of Deutsch problem explained in Section 4. No further operation like Hadamard transformation $H$ in the last step to identify $\phi_E = |0\rangle$ or $\phi_O = |1\rangle$ is required. As can be seen from Figure 4(a), such decision work can be done at the very early stage of time evolution. For two states $|\phi^-\rangle$ and $|\phi^+\rangle$, we show the feedback law $p_x$ in Figure 5 and the force $F_x = p_x$ in Figure 6. The initial trends in an expanded time are shown in (a) in these Figures 4, 5 and 6. Our feedback control system is periodic due to the periodic wave function (12). We calculate $T = \frac{2\pi H_0}{E_0 - E_E} = 6.9$ s consistent with those shown in (b) of Figures 4, 5 and 6. The force $F_x$ is about 20 N at maximum as shown in Figure 6. Therefore, the omni-mobile robot with mass $\sim 1$ kg can be moved without any problem by using an everyday electromagnet or DC motor. In our method, $|x\rangle$ can be directly “measured” without passing through $H$ transformation to determine $|\phi^-\rangle$ or $|\phi^+\rangle$. As far as this $|\phi^-\rangle$ or $|\phi^+\rangle$ determination process is concerned, we get approximate results: clock $f \sim T^{-1} \sim 0.14$ [Hz] and power $P_T = f \int |x|F_xdx \sim 0.0002 \sim 3.35$ W, consistent with those by dimensional analysis done before.

6. Conclusion

A causal formulation of quantum mechanics helped us to show how to determine the wave function parameters by monitoring particle trajectory. This means that quantum computation using a device that follows classical mechanics at the same time does not have to be so large has been embodied. Deutsch problem was effectively solved by the method in the form that no final Hadamard gate is required. This work is the first step towards the goal of truly autonomous robots that act according to their emotions as well as logic.

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