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Automation of Quantum Braitenberg Vehicles Using Finite Automata: Moore Machines

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Abstract Since the advent of quantum computation, there have been attempts to apply quantum mechanics to robotics and develop quantum robots. In this paper, we discuss the working of classical Braitenberg vehicles and the various problems which lead us to propose a novel improvement by automating the it using classical finite automata, Moore machines. We then improve by introducing an intrinsic nature to it such that it stops its motion without requiring external signals, by using entanglement. This leads to our design of a quantum automated Braitenberg vehicle which we improve by incorporating the possibility of external control over its movement. We implement the circuits in IBM Quantum Experience and obtain results matching our theoretical predictions. This paper makes the following contributions: an experimental verification of the quantum logic with reasonably good results despite decoherence and errors in quantum gate applications, the idea of introducing intrinsic behaviour using quantum mechanics, the idea of flexibility in developing man-

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ual external controls, and achieving better results than classical robots using lesser number of gates.

Keywords IBM Quantum Experience, Quantum Robots, Automated Classical Braitenberg vehicles, Automated Quantum Braitenberg vehicles, Finite Automata, Moore Machines

1 Introduction

The notion that information is physical was first introduced by Rolf Landauer in 1996 [1]. Since then, several investigations have been made to analyze ways to use the physical nature of *classical* information. In 1980, Paul Benioff first suggested the idea of quantum information [2]. The idea was furthered by Feynman where he reasoned about physical simulations on quantum computers, motivated by the fact that it is hard to perform matrix operations on a classical computer and that a quantum computer would better perform these operations [3]. Manin, in his textbook *Computable and Uncomputable* also discussed similar ideas [4]. The quantum analogue of classical Turing machines was developed by Deutsch [5].

The advent of *quantum* information led to the question that how we can manipulate the physical nature of quantum information and *what tasks can we accomplish given a physical resource* [6]. The several applications of quantum information have been possible due to the quantum effects: superposition, entanglement, and violation of Bell's inequality [7], that have no counterparts in classical information theory. Benioff [8] stated a quantum robot as a mobile quantum system equipped with a quantum computer and ancilla system. A quantum robot observes the environment, does measurement on the observables, and takes some deterministic/non-deterministic action based on the measurement. In this process, a quantum robot takes advantage of quantum mechanics, quantum computation, and quantum algorithms to gain some advantage and unique abilities over a classical robot.

There have been several recent advancements in developing quantum robots. Dong *et. al.* [9,10] created learning algorithms based on quantum mechanics for a quantum robot. Zeno and Francois [11] applied *eigenlogic*, a formulation of propositional logic to enlarge behaviour possibilities and associated decisions of simple agents. Zizzi [12] adopted a quantum metalanguage to control quantum robots, and demonstrated a physical implementation of the same.

In this paper, we use the idea of classical Braitenberg vehicles [13] and convert it into an idea of quantum vehicles/robots. Braitenberg demonstrated a vehicular agent consisting of sensors and motors connected to wheels. The sensors measure some stimulus and based on some classical combinational/sequential logic, the motors may work in some configuration and may not work in others, thus depicting intelligent behaviour.

We first discuss a Braitenberg vehicle with classical combinational/sequential logic and point out the need for automation. We then convert it into a classical

Braitenberg vehicle with automated logic using classical finite automata, precisely Moore finite automata machines [14]. We then discuss a disadvantage in the above automation and attempt to remove it using quantum logic and theoretically describe the movement of a robot under a certain sequence of input and output states. Finally, we present an improved design that includes manual control over the automated vehicle whenever desired.

IBM has developed different types of prototypes of quantum processors and available by a free web based interface called IBM Quantum Experience (IBM QE). Researchers have used it to demonstrate and run a variety of quantum computing experiments [15,16,17,18,19,20,21,22,23,24]. Here, we use the IBM QE platform to verify the results by designing and performing the experiment on the quantum chips.

The paper is organized as follows. In Section 2, we introduce the basic notion of a classical Braitenberg vehicle and discuss some disadvantages. In Section 3, we proceed to automating the Braitenberg vehicle to remove these disadvantages. In Section 4, we develop and discuss an automated quantum Braitenberg vehicle, inspired by the work of Raghuvanshi *et. al.* [25]. In Section 5, we develop an improved version where we introduce an external control mechanism over the movement of the robot. Finally, in Section 7, we compare the classical and the quantum automated Braitenberg vehicles and deduce our results.

2 Classical Braitenberg Vehicle

The importance of classical Braitenberg vehicles is because of the simple circuitry leading to complex behaviour, depending on the inputs received by the sensors. A schematic of a classical Braitenberg vehicle is given in Fig. 1.

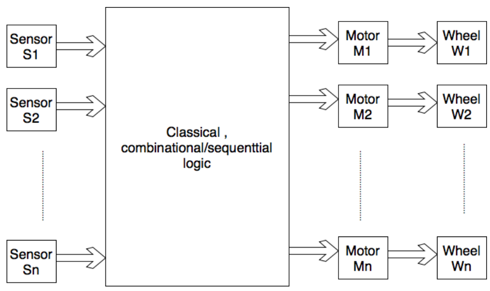

Fig. 1 Schematic of a classical Braitenberg vehicle. The sensors receive the light signals, turn to logic 1, and feed the inputs to the combinational/sequential logic. The motors receive the outputs and drive the wheels.

A generalized n sensor vehicle can be used to drive a n motor vehicle. In the subsequent discussions, we take these sensors to be simulated by light such that the inputs to the combinational/sequential logic take a value 0 in absence of light and 1 in the presence of light. The logic is designed such that in the absence of light, the motors stop, while in the presence of light, the motors work as determined by the logic implemented in the internal circuitry. For our purpose, we take a simplistic design such that motor M_i works when sensor S_i receives a signal, and driving wheel W_i forwards.

There is an obvious disadvantage here. The computation of the implemented logic is fast, thus it requires the signals to be inputted continuously. An added disadvantage could arise depending on the physical implementation of the machine. If the sensors are open to the atmosphere, the light used to stimulate them cannot lie in the range of frequencies coming from the atmosphere. Generating light of frequencies different than that of those present in the atmosphere is especially tough when it has to be done continuously.

A source of error in controlling the robot arises if the physical implementation is not robust enough to prevent unintentional light signal to some sensor when signalling some other sensors, causing an unintentional impetus to the motor. The probability of such errors increases if light inputs need to be to given to the sensors continuously.

We propose a solution in the following section that eliminates the need to continuously provide light input to the sensors.

3 Automation of classical Braitenberg vehicle

In this section, we propose a novel architecture using finite automata to reduce the need to continuously provide light inputs to the sensors. We propose a Moore machine implementation, depicted by the schematic in Fig. 2, and provide a sample run of the robot.

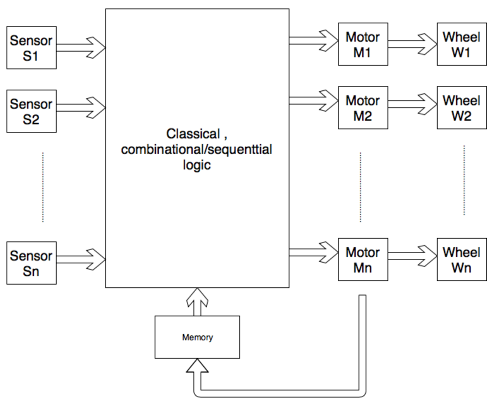

Fig. 2 Schematic of a classical Braitenberg vehicle using Memory, which is implemented by a Moore machine. Here it can be observed how the motor behaviour is dependent on outputs only, and not on the inputs.

Table 1 Truth table for automated Braitenberg vehicle. All symbols have their usual meaning. Movement represents the deterministic action taken by the robot based on the outputs M1 and M2, which in turn are governed by sensors and the memory

S1	**S2**	**M**	**M1**	**M2**	**Movement**
0	0	0	0	0	Nothing
0	0	1	1	1	Forward
0	1	0	0	1	Right
0	1	1	0	1	Right
1	0	0	1	0	Left
1	0	1	1	0	Left
1	1	0	1	1	Forward
1	1	1	0	0	Stops

A Moore machine is a finite automata machine where the output states are also considered in the input in the next iteration of the logic; the outputs however, depend only on the logic performed by the circuitry designed and not on the input states.

Now we present a sample run of such an automated robot. We assume a robot with two sensors S1 and S2 and two motors M1 and M2 connected to two wheels W1 and W2 respectively. We implement the Moore machine (denoted in subsequent discussion in this section as M) such that when $M = 1$, the motors are in movement and the robot moves forward and when $M = 0$, the motors depend on the external light signals for their movement.

Initially, the robot is at rest. Some signal (either S1 or S2 or both) is provided and the motors behave such that M1 = 1 for S1 = 1 and M2 = 1 for S2 = 1. After this iteration, the external light signals are withdrawn. The memory stores $M = 1$ and that is fed as input in the next iteration, driving the robot forward by M1 = 1 and M2 = 1 in subsequent iterations. Note that this output state is caused solely by $M = \mathit{1}$ stored in memory. If a need arises to change the direction of the robot, requisite external light signal (S1 = 1 or S2 = 1) may be provided. If there is a need to stop the robot, both external signals can be activated (S1 = 1 and S2 = 1). The results are depicted in Table 1.

We now show it is indeed possible to construct such a machine. We reduce the expressions for M1 and M2 using Karnaugh maps. The reduced expression derivation for M1 is given in Fig. 3. The reduced expression for $M1$ is $M1 = S2^{'}M + S1M^{'}$. where $^{'}$ denotes the complementary state of the variable.

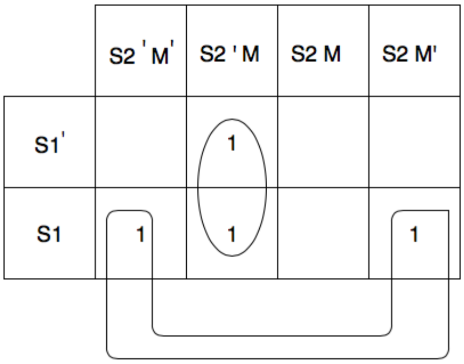

Fig. 3 Karnaugh map reduction for M1. There are two pairs or two essential prime implicants, leading to elimination of one variable in the Sum Of Product form in the reduced expression.

Likewise, state reduction of $M2$ is given in Fig. 4.

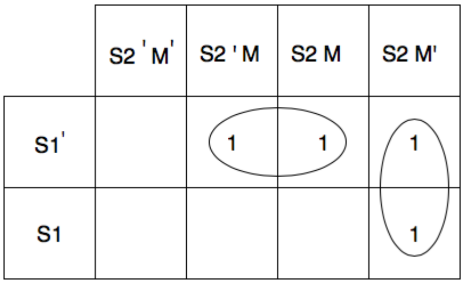

Fig. 4 Karnaugh map reduction for M2. Similar to Fig. 3, there are two essential prime implicants and therefore one variable gets eliminated in the final reduction of the expression.

The reduced expression for $M2$ is $M2 = M^{'}S2 + MS1^{'}$. where $^{'}$ denotes the complementary state of the variable.

4 Automated Quantum Braitenberg Vehicle

The quantum equivalent of classical automated Braitenberg vehicle can be obtained by using an equivalent quantum circuit in place of the combinational/sequential circuits used in Fig. 2. We present here a different Braitenberg machine using quantum circuitry, with the same external configuration of two sensors S1 and S2, and two motors M1 and M2 connected to two wheels W1 and W2 respectively. We experimentally realized the machine on IBM Quantum Experience platform by designing quantum circuits. The results are depicted in Table 2. M depicts the measurement of the qubit corresponding to *memory*. It is used as the input to the memory qubit in the next iteration.

Table 2 Truth table for automated Braitenberg vehicle. All symbols have their usual meaning, and Mp denotes memory from previous iteration and Mn denotes the memory to be inputted to next iteration.

S1	**S2**	**Mp**	**M1**	**M2**	**Mn**
0	0	0	0	0	0
0	0	1	001 or 110		
0	1	0	0	1	0
0	1	1	011 or 100		
1	0	0	1	1	1
1	0	1	001 or 110		
1	1	0	1	0	1
1	1	1	011 or 100		

Note that the outcome of the experiment is deterministic when $M = 0$, and non-deterministic or entangled when $M = 1$. Now we present a simple operation this quantum robot can perform. Suppose S1 = 0, S2 = 0, and M = 0 at the start, leading to M1 = 0, M2 = 0, and M = 0. The robot does not move. But M is stored in memory and is fed to the memory qubit as the input in the next iteration. Now we shine light on the robot such that S1 = 1, S2 = 0. Since M = 0 from the memory, the result is deterministic, and we get the state M1 = 1, M2 = 1, and M = 1. So the motors move for this iteration, and the memory stores M = 1 to be fed into memory qubit for the next iteration.

Now we turn off the external light signals. So the current input state is S1 = 0, S2 = 0, and M = 1 (from memory). This leads to the probabilistic model depicted in Fig. 5. It can be easily seen that we get states M1 = 0, M2 = 0 and M = 1 or M1 = 1, M2 = 1, and M = 0.

If the latter case M1 = 1, M2 = 1, and M = 0 is obtained, the motors move in this iteration, and for the next iteration, the input to the quantum logic is S1 = 0, S2 = 0, and M = 0, so the robot stops. If the former case M1 = 0, M2 = 0, and M = 1 comes up and since the lights are still off, the input to the quantum logic in the next iteration is S1 = 0, S2 = 0, and M = 1, which leads to the probabilistic model depicted in Fig. 5.

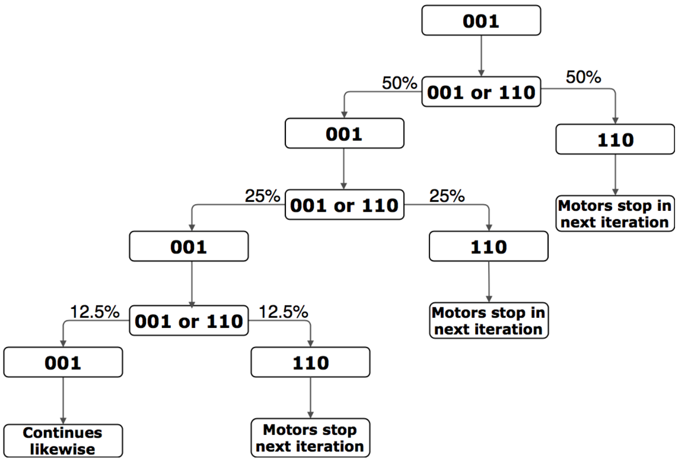

Fig. 5 Probabilistic model for one of the entangled states. The subsequent probabilities in the left branch are the probabilities of event occurring given the parent node event has occurred.

Note that the probability of eventually stopping is increasing with every iteration. It is 50% in the first iteration, 75% in the second iteration, 87.5% in the third iteration, and so on. Note that the state M1 = 1, M2 = 1, M = 0 for no incoming light signal means that the motors receive some incremental impetus in *this* iteration and do not receive any more impetus in the next iteration, eventually making friction to stop the robot. The experiment done on IBM Quantum Experience used the circuit depicted in Fig. 6. q[0] corresponds to S1, q[1] corresponds to S2, and q[2] corresponds to M, the *memory*. Note that to reduce the number of qubits, we have designed the logic such that the measurement of q[0] gives the state of M1, the measurement of q[1] gives the state of M2, and q[2] remains as the memory qubit.

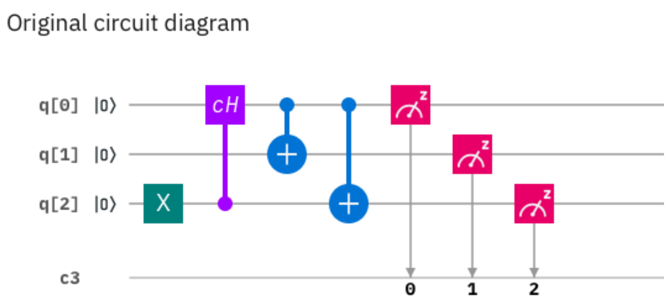

Fig. 6 Circuit designed to test the state S1 = 0, S2 = 0, M = 1 corresponding to the state that results in entanglement and the probabilistic model in Fig. 5.

Here we describe the functionality of the quantum gates used in the above Fig. 6 and in the Fig. 11.

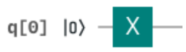

Fig. 7 The IBM quantum experience gate symbol for quantum NOT gate. It flips the state of the qubit it is applied on.

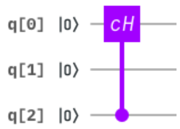

Fig. 8 The IBM quantum experience gate symbol for quantum controlled-Hadamard gate. Whenever the *control* qubit q[2] is $|1\rangle$, *target* qubit q[0] is set to $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$. In general, the *control* qubit is the solid dot while the *target* qubit is the solid box.

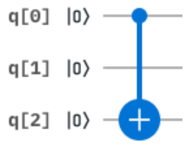

Fig. 9 The IBM quantum experience gate symbol for quantum controlled-NOT gate. Whenever the qubit q[0] is $|1\rangle$, qubit q[2] is flipped.

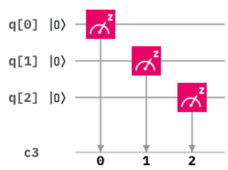

Fig. 10 The IBM quantum experience gate symbol for quantum measurement operation. In general, the solid boxes signify the qubit to be measured, and the result of the measurement is stored in the classical register positions 0, 1, and 2.

5 Improvement to the Automated Quantum Braitenberg Vehicle

It is shown in the previous section that the probability of stopping increases with every iteration, leading to the robot eventually stopping. There might be, however, a case where we need a mechanism to manually stop the robot. Observe from the Table 2 and from Fig. 5 that whenever $M = 1$, the outcome is non-deterministic or entangled, and one of those entangled states leads to $M = 1$ in the next iteration and so on.

We introduce in Fig. 11 a mechanism to erase the memory. We introduce a *control* qubit which erases the memory when it receives the signal, leading to 72.461% probability that the system stops in *that very* iteration. In Fig. 11, q[0] corresponds to S1, q[1] corresponds to S2, q[2] corresponds to *control* qubit, and q[3] corresponds to M, the *memory*. Note that to reduce the number of qubits, we have designed the logic such that the measurement of q[0] gives the state of M1, the measurement of q[1] gives the state of M2, and q[2] remains as the memory qubit.

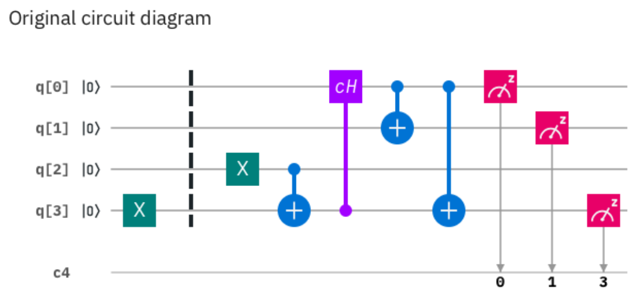

Fig. 11 Improved circuit designed to test the *manual stopping mechanism*: if q[2] receives a signal, the operation stops.

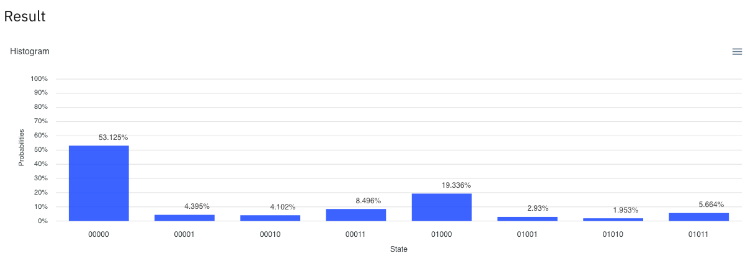

Fig. 12 It is seen that the two most probable states are the configurations that shall lead to immediate stopping of the robot, by setting the memory bit to 0 for the very next iteration.

The results obtained in Fig. 12 are from ibmqx4 back-end of the IBM quantum experience, implying the circuits give good results on fully quantum machines, despite the decoherence and errors in application of the gates. Here we have benefited from our design where we had reduced the number of qubits involved by designing the circuit such that the measured bits for the qubits q[0] and q[1] (designed for light signal inputs S1 and S2) are delegated as the outputs M1 and M2, thereby removing the need for separate qubits for M1 and M2. Such optimizations are essential to any quantum circuit design since reducing the number of qubits and quantum gates can reduce the influence of decoherence, and bring the results in acceptable and implementable range(as in our design).

6 Role of entanglement

Entanglement plays a deeper role in the very construction of the logic of the robot. We discuss the role of entanglement in two scenarios: deterministic operation of the robot (when *memory* $M = 0$) and the non-deterministic operation of the robot (when *memory* $M = 1$).

In the deterministic operation of the robot, entanglement allows to create the logic that drives the robot, as desired according to table 2. Based on the state of the *control qubit*, the CNOT gates modify the state of the *target qubits*, as seen in Figs. 6 and 11, thereby entangling them and implementing the desired logic.

Entanglement has also been used to introduce intrinsic behaviour into the robot by carefully planning the *control* and *target* qubits of the CNOT operations, and coupling the entanglement with superposition (implemented with the *controlled Hadamard* gate in Figs. 11 and 6, whenever the *memory* $M = 1$); hence creating the non-deterministic operation of the robot. This intrinsic behaviour introduced due to entanglement and superposition allows superiority of quantum automated Braitenberg vehicles over their classical counterparts, as detailed below.

It is observed from the above discussions on classical automated Braitenberg vehicles and from table 1 that given the *memory* $M = 1$ and the absence of external light signals, the vehicle tends to move forward at full throttle. It is therefore required to apply external light signals to both sensors simultaneously to be able to stop the vehicle. We note this is not required for the quantum automated vehicle. They have an intrinsic tendency to stop after some iterations, as can be seen from the probabilistic model in Fig. 5. This intrinsic tendency comes from *entanglement*, an entirely quantum phenomenon. Entanglement causes the outputs of the quantum logic to be *non-deterministic* whenever *memory* $M = 1$. We note one of the probable outcomes of such entanglements causes the inputs in the next iteration to be S1 = 0, S2 = 0 (since external light signals are absent) and M = 0. Such intrinsic nature to stop can be helpful in variety of situations, for instance, making the vehicle more robust to high speeds and accidents.

Based on the planning of the logic, entanglement and superposition may be used to introduce such non-deterministic, intrinsic nature into the robots. Such non-deterministic behaviour can provide superiority to the quantum robot over a classical robot, based on the use case implemented.

7 Discussion and Conclusion

In this paper, we have presented an overview of classical Braitenberg vehicles. We discussed challenges in the practical implementation of such vehicles, and provided a solution using automation through finite automata, Moore machines.

We then presented the quantum version of automated Braitenberg vehicles and discussed how entanglement leads to an intrinsic nature in the functioning of the robot. We have discussed this nature and its implications in section 6. Finally we demonstrated an improvement to the design by introducing a manual control method of *most likely* stopping the robot in the very iteration the signal is applied to the *control qubit*.

The classical Braitenberg vehicles are interesting concepts for the fact how they let simple circuitry to introduce complex behaviour in robots. Quantum Braitenberg vehicles are, however, a class apart. A quantum robot can take advantage of quantum phenomena to exhibit probabilistic behaviour, like the one we demonstrated above. It is also to be noted if the classical circuitry of the expressions we derived in Figs. 3 and 4 are implemented using AOI (And, OR, Inverse or NOT) logic, we require more number of gates than we do in the quantum Braitenberg vehicle circuitry. We conclude that as the complexity of the circuitry increases, one would require less number of gates in the quantum implementation than that in the classical one.

Robotics has been the center of academic and engineering attraction ever since the beginning of technological development. When it comes to quantum robotics, the strange properties of quantum mechanics makes quantum robotics an interesting and useful domain. As quantum architecture increases in efficiency thereby increasing coherence time and the rate of errors in application of quantum gates decreases, we are set to witness astonishing progress in the field of quantum robotics.

Acknowledgments

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