Quantum Robots for Teenagers

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Abstract

Extending the ideas of Quantum Braitenberg Vehicles from [14], we present here a family of Lego robots controlled by multiple-valued quantum circuits. The robots have at most 6 degrees of freedom (motors) and 6 sensors. Their basic architecture is a generalization of robots from [16] to more versatile multiple-valued quantum automata (simulated in software). We believe that building robots with "quantum brains" is an excellent future application of quantum computing and now it helps students to learn principles of quantum circuits. We present a one-year project in "quantum robotics for teenagers". Our project brings research and educational perspectives, which are both presented in this paper.

1. Introduction

Contrary to opinions of some "popular science writers" quantum computing is not science fiction - quantum circuits are already used commercially for secure communication. The results of the famous Einstein-Podolsky-Rosen thought experiment [7] are already well-established and provide a base of operations for quantum circuits, communication, etc. The strange and fascinating world of quantum computing is now widely open for investigation and commercialization. It is believed that quantum computing will begin to have a global impact around year 2010. We have an interest in two questions: 1) how quantum computers and quantum information concepts can be used in the area of robotics, 2) how the concepts of quantum computing can be taught to future inventors and users of this technology who are now middle school students. This paper is related to both questions.

A theoretical concept of a Quantum Robot has been introduced by Benioff [10,11] but his papers do not show practical examples. While the quantum robot of Benioff operates in a strictly quantum world, the robots introduced by our laboratory in [16] are controlled by quantum circuits (or their software models on standard computers) but they can use normal sensors and effectors and thus operate in macro-world like standard robots. In contrast to Benioff's Quantum Robots, the robots introduced in this paper should be called Quantum Controlled Robots to emphasize that only their controls are quantum but sensors and effectors are classical (this is a sub-class of robots introduced in [16]). A quantum circuit in this research is only simulated in Robot C- language [15] software but sooner or later robots controlled by truly quantum processors are bound to appear. They will use entanglement, superposition (parallelism), Heisenberg's Uncertainty Principle, EPR circuits, and all the laws of physics that make quantum computers and information so different from those of the classical realm. We will model the EPR (Einstein-Podolsky-Rosen) circuit here and we use it to control a robot which we call an "EPR Robot". This helps to visualize the concept of entanglement as certain constraint on robot's behavior – an easy concept to grasp.

Moreover, in our forthcoming work, we use the well-known Grover algorithm [7] for robot action planning, problem solving and vision, which, in case of using a truly quantum computer, would speed up these tasks considerably. We also use a generalized Deutsch-Jozsa algorithm [7] for robot vision tasks using spectral transforms [7]. When coupled with truly quantum devices, the quantum robots introduced by us would execute some perception tasks several orders of magnitude faster than any conceivable robots built using existing technologies [17,18].

The paper is organized as follows. Section 2 introduces classical Braitenberg Vehicles and few examples of our Lego Robots. Section 3 is a brief introduction to quantum and reversible robot controllers. Section 4 introduces Quantum Braitenberg robots. The presented paper has two aspects. First, it is a research paper that introduces new ideas and discusses their realization. Second, this is a paper written by three gifted teenagers mentored by their coach – a university professor. Section 5 presents Lego robots built by the teenagers. The didactic aspects of this project are next presented in section 6. Finally section 7 concludes the paper. Although we tried to make the paper self-contained, the reader interested in more information on quantum circuits may need to consult quantum textbooks like [7].

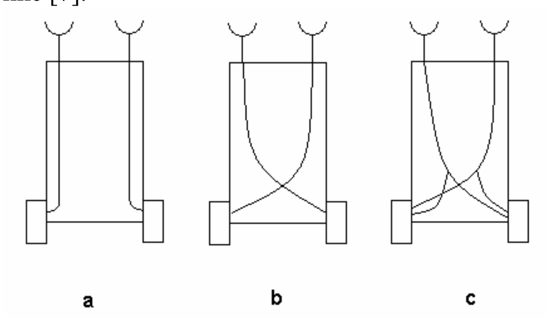


Fig 1 Three simple Braitenberg Vehicles

2. Classical Braitenberg Vehicles

Valentino Braitenberg wrote a revolutionary book titled Vehicles: Experiments in Synthetic Psychology (Publisher: Cambridge, Mass. MIT Press, 1986), [2]. In the book he describes a series of thought experiments. It is shown in these experiments that simple systems (the vehicles) can display complex life-like behaviors far beyond those which would be expected from the simple structure of their "brains." He describes a law termed the "law of uphill analysis and downhill invention". This law explains that it is far easier to create machines that exhibit complex behavior than it is to try to build the structures from behavioral observations. By connecting simple motors to sensors, crossing wires, and making some of them inhibitory, we can construct simple robots that can demonstrate behaviors similar to fear, aggression, affection, and others. The original vehicles use only analog signals or Boolean Logic, but we generalized these ideas to multiple-valued, fuzzy, probabilistic, and quantum logic and we designed emotional robots that combine various types of logic – a task which is easy when all control is built in software.

The first vehicle (Fig 1) has two sensors and two motors, at the right and left. The vehicle can be controlled by the way the sensors are connected to the motors. Braitenberg defines three basic ways we could possibly connect the two sensors to the two motors.

a) Each sensor is connected to the motor on the same side.

b) Each sensor is connected to the motor on the opposite side.

c) Both sensors are connected to both motors.

Type (a) vehicle will spend more time in places where there are less of the stimuli that excite its sensors and will speed up when it is exposed to higher concentrations. If the source of light (for light sensors) is directly ahead, the vehicle may hit the source unless it is deflected from its course. If the source is to one side, then the sensor nearer to the source is excited more than the other and the corresponding motor turns faster. As a consequence, the vehicle will turn away from the source. Turning away from the source (a shy behavior) is illustrated on the left in Figure 2.

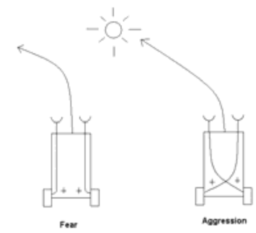


Fig 2: The vehicle at left avoids light while the vehicle at right follows light.

We can observe another type of vehicle, type (b), with a positive motor connection. There is no change if the light source is straight ahead, a similar reaction as seen in type (a). If it is to either side, then we observe a shift in the robot's course. Here, the vehicle will turn towards the source and eventually hit it (aggressive behavior) .

Next, Braitenberg presented thought experiments with increasingly complex vehicles built from the standard mechanical and electrical components of his time. Braitenberg's goal was to explore the nature of intelligence and psychological ideas that were not related to quantum control. Even so, more and more intricate behaviors emerge from creating various interactions between components; see [1,2,3,5,8,9]. The "vehicles" presented here are not merely mobile wheeled robots like those from [2], but a humanoid biped or a human torso with head, so that we can create much more interesting and sophisticated movements, although the general principle of behavioral robotics as illustrated in Braitenberg Vehicles (the evolution of complex behaviors from simple descriptions) remains. As will be discussed, multiple-valued quantum automata hold many advantages over simple binary combinational circuits.

In last year, the teenage students built several Lego robots, most of them using the old Lego sets: 1) several 2-wheeled and 4-wheeled vehicles similar to classical Braitenberg (Arushi), 2) robot head to illustrate human-like emotions (Arushi and Yale), 3) a walking biped (Michal). The new 2006 NXT Lego set gives much better opportunities which are being now investigated.

3. Practical Use of Quantum Formalisms in Robot Control Design

In quantum circuits, to calculate a quantum state after the gate, the unitary matrix of the gate is multiplied by the vector of the state before the gate. A general purpose controlled quantum gate is shown in Figure 3.

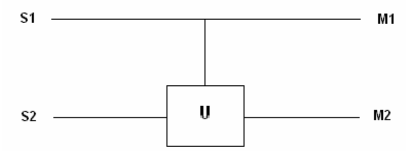


Fig 3: A general-purpose controlled quantum gate. U is arbitrary one-qubit quantum operator.

In the case of binary control bit S1, the gate operates as follows:

if S1 = 0 then M2 = S2
if S1 = 1 then M2 = U (S2)

In the case of ternary control, the gate operates as follows:

If S1 = 0 or S1=1 then M2 = S2
If S1=2 then M2 = U(S2) where U is an arbitrary binary or ternary quantum operator.

Fig. 4 presents the truth table of the ternary gate, assuming that the operator U is adding 1 modulo 3. We assume the following interpretation of ternary signals in sensors S1 and S2: 0 – nothing, 1 – little, 2 – much. This applies also to the output signals to motors M1 and M2 (arrangement as in Fig. 1). In Fig. 4, we describe the behavior of a Quantum Robot with this gate as its brain. These gates are realizable directly in quantum devices, while gates like Toffoli are realized using many connected 2-qubit quantum controlled gates. A quantum gate operating in parallel with another quantum gate will increase the dimensions of the quantum logic system represented in matrix form. This is due to application of the Kronecker (tensor) product of matrices to the system. Kronecker Matrix Multiplication is responsible for the growth of qubit states such that N bits correspond to a superposition of r^N states, whereas in other digital systems, N bits correspond to r^N distinct states. The number r denotes the base (radix) of logic, being 2 for binary and 3 for ternary logic.

S1	S2	M1	M2	Robot behavior
0	0	0	0	No light. Robot stops.
0	1	0	1	Little light from left. Robot turns slowly away from light. Makes right turn.
0	2	0	2	Much light from left. Robot turns quickly away from light. Makes right turn.
1	0	1	0	Little light from right. Robot turns slowly away from light. Makes left turn.
1	1	1	1	Little light in both sensors. Robot moves slowly forward.
1	2	1	2	Little light from right, much from left. Robot turns away from light using larger circle.
2	0	2	1	No light from left, much from right. Robot turns left slowly
2	1	2	2	Little light from left, much light from right. Robot moves forward quickly.
2	2	2	0	Much light in both sensors. Robot turns quickly left.

Fig 4: Behavior of Braitenberg Vehicle with gate from Figure 3 used as a controller, (S1= right light sensor, S2= left light sensor, M1= right motor, M2= left motor), and U being the operator of adding 1 modulo 3

The Kronecker Product of two one-qubit gates is:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \otimes \begin{bmatrix} x & y \\ z & v \end{bmatrix} = \begin{bmatrix} a\begin{bmatrix} x & y \\ z & v \end{bmatrix} & b\begin{bmatrix} x & y \\ z & v \end{bmatrix} \\ c\begin{bmatrix} x & y \\ z & v \end{bmatrix} & d\begin{bmatrix} x & y \\ z & v \end{bmatrix} \end{bmatrix} = \begin{bmatrix} ax & ay & bx & by \\ az & av & bz & bv \\ cx & cy & dx & dy \\ cz & cv & dz & dv \end{bmatrix}$$

A quantum gate in series with another quantum gate will retain the dimensions of the quantum logic system. The resultant matrix is calculated by multiplying the operator matrices in a reverse order.

Below, we show the notation and the unitary matrix of a very important quantum gate – the Hadamard gate (Fig. 5). This is a “truly quantum” gate that cannot be realized in a binary or permutative reversible circuit. This is in contrast to permutative gates (described by permutative matrices) that can be realized by standard reversible logic circuits.

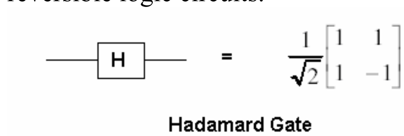


Fig 5: Hadamard gate notation and its unitary matrix.

An example of a binary unitary and permutative matrix is the Feynman gate (Fig. 6). A permutative matrix has exactly one ‘1’ in every row and column. MV Feynman gate uses modulo addition of A and B, ternary in our case.

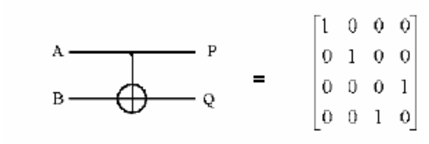


Fig. 6. Feynman gate notation and its unitary

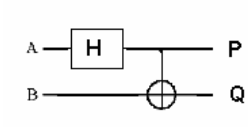
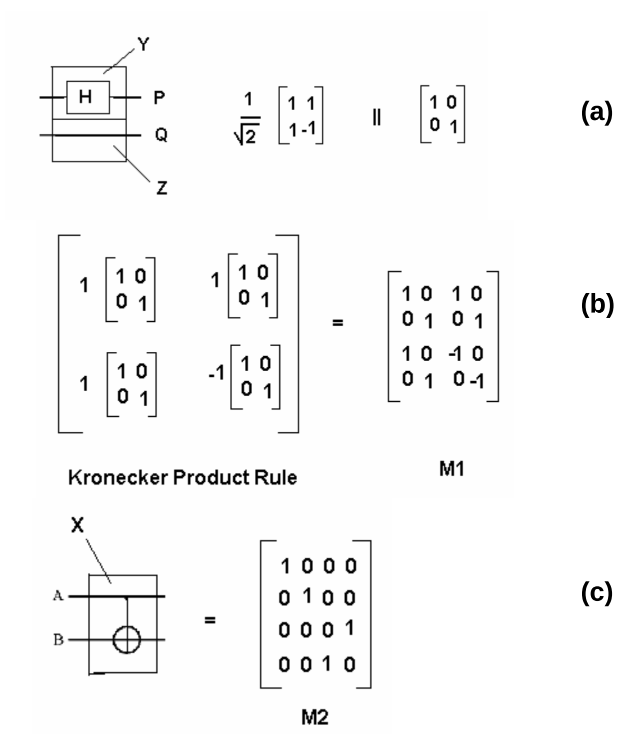


Fig. 7: The quantum controller for the EPR robot. This circuit produces entanglement that can be analyzed by robot behaviors

The quantum circuit from Fig. 7 can be split into 3 circuits as shown below. Here, the Hadamard gate (gate Y in Figure 8a) is connected in parallel to a wire (gate Z in Figure 8a). Next, the parallel connection of gates Y and Z is in a series with the Feynman gate (gate X in Figure 8c). We need the Kronecker Product to calculate the parallel connection and standard matrix multiplication to calculate the serial connection. This is shown step-by-step in Figure 8. Similarly ternary entanglement circuits with Chrestenson (Fourier) gates [17] are analyzed and used for robot controllers.



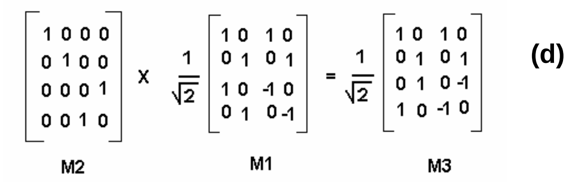


Fig 8: a) Calculation of parallel connection of gates H and wire b) Calculation of Kronecker Product of Hadamard and wire using their unitary matrices. c). Unitary matrix of Feynman gate in the entanglement circuit. d) Final calculation of the unitary matrix of the entanglement circuit by multiplying matrices of Feynman gate(M2) and a parallel connection of H and wire (M1) in reverse

We will now analyze the behavior of the circuit from Fig. 7. Suppose that we set each input A and B to state 0. Thus, the input state vector is |0> x |0> = |00> = $[1\ 0\ 0\ 0]^T$, where T denotes the transpose matrix. Now, we want to calculate the quantum state at the output of the entanglement circuit at points P and Q. To do this, we must multiply the matrix M3 (a linear operator) from Fig 8d by vector $[1\ 0\ 0\ 0]^T$, which leads to vector $1/\sqrt{2}[1\ 0\ 0\ 1]^T$. For a better visualization, this last vector can be rewritten in Dirac notation as: $1/\sqrt{2}$ |00> + $1/\sqrt{2}$ |11>. This means that we obtain a measurement of state |00> with probability ½ and a measurement of state |11> with probability ½. Measuring the first bit as |0>, we automatically know that the second bit is also |0> due to the states being unique and unfactorizable. Similarly, measuring the second bit as |1>, we know that the first bit is in state |1>. This strange phenomenon is called entanglement. Assume now that signals A and B come from sensors S1 and S2 as in Fig. 1a, and P and Q go to motors M1 and M2. Assume also that 0 signifies no light to the sensor and 1 is light, and that 0 is no motor movement while 1 is full speed forward movement. If there is no light in front of the robot, the robot will randomly either stay stable (both motors have 0) or will move forward (both motors will have 1). The combinations 01 and 10 for the motors are not possible because their corresponding eigenstates have null amplitudes. The robot cannot thus turn right or left in this situation. It is left to the reader to analyze behaviors of this robot for every possible binary input combination. Next the reader can analyze what will happen if gate H is removed from the controller. Can the robot turn left and right? Does there exist an entanglement between states |01> and |10>, which would mean that the robot would never stop or go straight but keep turning left and right randomly? When? This is the kind of challenge questions to ask the students. Another challenge would be to guess the controller circuit from the observed behaviors of the robot.

Observe that if we had two H gates in parallel as the controller and there were no light present, then every combination of motors 00 (stop), 01 (turn left), 10 (turn right), and 11 (go forward) would be possible with equal probability. When measured, the Hadamard gate works as ideal random number generator. It can be controlled by an arbitrary quantum signal that allows us to control the probabilistic and entangled behaviors of the robot. Suppose that the Hadamard gate in Fig. 7 is controlled by one more wire D. If D = 0, the circuit is just a Feynman gate, which means that when both sensor inputs A and B are 1, signal P is 1 but signal Q is 0 (since $1 \oplus 1 = 0$) and the vehicle will turn right. Similarly, we can find deterministic behaviors of the vehicle for any input combination. However, when D = 1, the Hadamard gate starts to operate and the circuit works as the explained earlier entanglement circuit.

It is well known that every combinational circuit can be transformed into a reversible (permutative quantum) circuit by adding so-called ancilla bits (constants to inputs and garbage bits to outputs). In this way, we can transform every standard automaton (Finite State Machine with binary flip-flops) to a (binary) quantum automaton. Because the Hadamard gate works as an ideal random number generator, with equal probabilities of signals 0 and 1 at its output, every probability with accuracy to $1/2^N$ can be generated with N controlled Hadamard gates. In the case of ternary quantum logic, the Chrestenson gates allow one to obtain probabilities with accuracy $(1/3)^N$.

This allows realization of an arbitrary probabilistic automaton in quantum (at the price of adding the ancilla bits). The deterministic automaton is a special case of a probabilistic automaton (a probabilistic automaton can be described by a probabilistic matrix, and a deterministic automaton by a permutative matrix). Finally, the quantum circuit (like our entanglement circuit) can be represented by a unitary matrix with complex numbers for transitions. Therefore, the quantum automaton is the most powerful concept of computing that is physically realizable at the time of this writing. It includes the combinational and probabilistic functions and automata as well as quantum combinational functions (quantum circuits) as its special cases.

This powerful concept has been, however, so far not investigated for robotics applications. There is no doubt that the Quantum Automaton Robot is much more powerful than a Braitenberg Vehicle, which fact we have observed by constructing and simulating multi-valued quantum equivalents of the known Braitenberg Vehicles (such as those from section 2). A simple Quantum Automaton Robot controller is shown in Fig. 10, and the table of its behaviors in Fig. 11. This controller can be used with similar but not exactly the same effects in all Lego robots from Section 5. Observe entanglement for S1=0, S2=0, C=1.

4. From Braitenberg Vehicles to Quantum Automata

Two variants of Braitenberg Vehicles are discussed in the literature. Binary vehicles that use operations such as AND, OR, NOT, etc. Fuzzy vehicles have continuous signals in interval [0,1] and operations such as Minimum, Maximum and fuzzy literals. The robots discussed here operate in combined binary, Multiple-Valued, reversible, probabilistic and quantum logics. An example of a generalized Braitenberg Vehicle is shown in Fig. 12a. The combinational block is now implemented in ternary quantum logic. The block sensors in the left transform also the signals to those acceptable by the ternary quantum computational block, and block actuators in the right transform to signals from the combinational block to those acceptable by actuators such as motors. Although Generalized Braitenberg Robot from Figure 12a uses only a combinational block between sensors and actuators, it is very natural to combine the Braitenberg Robot diagram with the Finite Automaton diagram to create Braitenberg Automaton Robot, as in Figure 12b. Now by extending the logic to fuzzy, quantum or other and generalizing a vehicle to an arbitrary robot, we obtain the concept of Braitenberg Automaton Robot, which may be binary, multiple-valued, reversible, quantum, fuzzy, probabilistic, etc. Having a set of generalized sensors (that includes sonars, vision, touch sensors) and a set of generalized actuators (that includes lights, motors, buzzers, etc.), one can create various generalized architectures as in Fig. 12 that very essentially generalize the original concept of Braitenberg, as well as the subsumption architecture from [8,9].

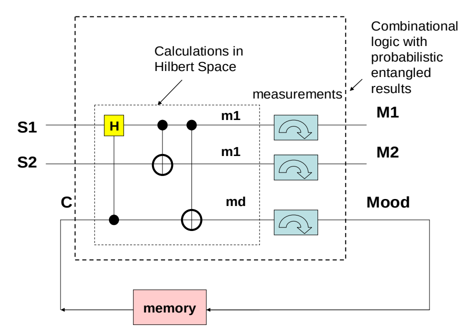


Fig 10: Logic Diagram of a Quantum Automaton. Use of Hilbert space calculations and probabilistic measurement is explained. Memory is standard binary memory, all measurements are binary numbers. All inputs/outputs are binary numbers. Mood is an internal state: Mood = 0 corresponds to rational nice mood and Mood = 1 to an irrational and angry robot.

It is amazing about original Braitenberg Vehicles – Figure 1, that small changes in rules (like crossing two wires) result in entirely different behaviors. It is similar to evolutionary algorithms where small changes in genotype can mean big changes in phenotype. The power of the Quantum Automata Robot is not only in its mathematical sophistication allowing it to accept more powerful languages than its classical binary logic counterpart concept. The power of the QAR concept results from the following observations:

(1) Deterministically controlled probabilistic behaviors are possible by adding quantum measurement devices after the combinational block but before the actuators or/and memory elements.

(2) Entangled behaviors are possible; the fundamental of quantum computing that is not reproducible in classical or probabilistic automata or robots.

(3) The property of "butterfly effect" between minimal circuit changes and behavior changes is even more dramatic than for standard Braitenberg Vehicles.

S1	S2	C	M1	M2	Mood
0	0	0	0	0	0 nice
0	0	1	$(000)_{1/2}$ or $(111)_{1/2}$		
0	1	0	0	1	0
0	1	1			
1	0	0	1	1	1 angry
1	0	1			
1	1	0	1	0	1
1	1	1			

Fig 11. Observation of entangled and deterministic behaviors of the robot. Some states are not completed – as a typical way of quizzing students.

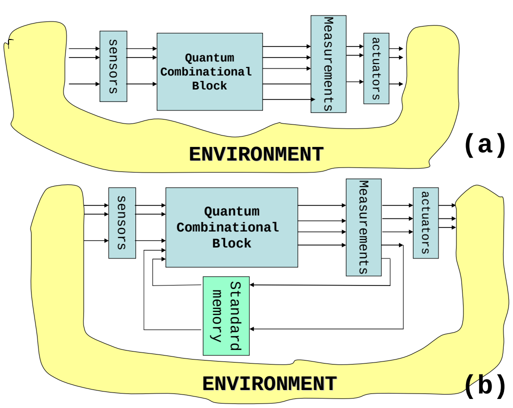


Fig.12: Generalized Braitenberg Robot (12 a) and Braitenberg Automaton Robot (12 b) may operate in both quantum and standard environment.

When several Quantum Automata Robots operate in the same environment, thus one can be perceived by others as an obstacle, friend or enemy, even more interesting group behaviors are observed. This way, an environment with a set of Braitenberg Quantum Robots becomes similar to a Game of Life or a Cellular Automaton. Patterns of behaviors of various robot societies can be observed and analyzed.

Although the examples given by Braitenberg use only simple robot drive with two motors and two sensors, a differential drive, Ackermann Drive or any other mobile robot drive can be used [14]. These concepts can be used for any type of robot kinematics; arm, torso, head or full humanoid. Finally the number of sensors and actuators can grow and we can replace the simple mobile robot as discussed above by a walking robot, humanoid robot, robot arm, robot head or whatever robot we can imagine. Our experiments with different robot drives and robot types confirm that the concept of emergent behaviors based on very small changes of behavioral rules remain very interesting and it becomes a research issue to be investigated.

In [16,18,20] various generalizations of automata and corresponding Braitenberg-like Vehicles were presented. Here we will focus on one variant only, that was realized in Lego designs. Gates such as an inverter, Feynman gate (CNOT), Toffoli gate (CCNOT) and Fredkin gate (controlled swap) are both reversible and quantum. However gates such as Hadamard or Square-Root-of-NOT cannot be realized in reversible (classical) technologies and are called here the truly quantum gates. They can be realized only in quantum devices or simulated, as presented here. In addition to these binary gates we use ternary gates such as controlled operations with any of 5 one-qubit permutative operations; +1, +2, (01), (02) and (12), ternary Toffoli gates, swap and Feynman gates, [13].

5. Quantum Robots from Lego

Writing classical, fuzzy and quantum circuit based behaviors for the Lego robot is a fascinating task for students [5,6,12]. We build controls based on mapping from sensors to behaviors (motor control sequences, sounds generated, lights). All behavior-circuits use standard signal values and generate standard normalized output signals for servos so that the user is not concerned at all with sensor calibration or motor control.

Quantumly Controlled Vehicles

Several Braitenberg Vehicles with different types of drives and sensor locations, some with quantum control were built [14] and their behavior analyzed (Fig. 13).

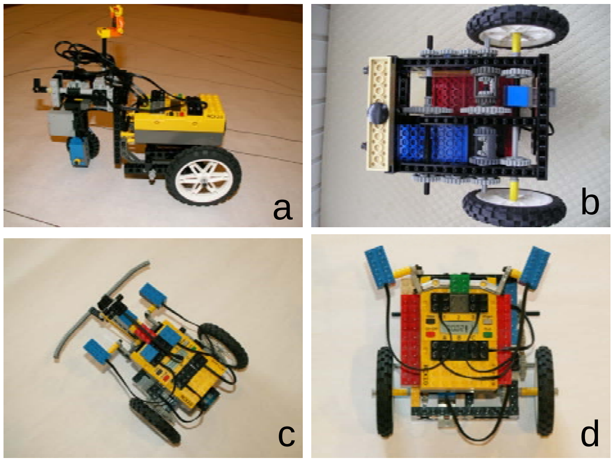


Fig 13: Braitenberg Vehicles with various kinematics and sensors. a) Tricycle Drive, b) Dual Differential Drive, c) shows Touch sensors, d) shows use of two Light sensors.

Mister Quantum Potato Head.

Happy and Sad emotions are shown on Mister Quantum Potato Head in Figure 14. Two touch sensors (top of head), 2 light sensors (near eyebrows) and 6 motors were used in this robot, together with two Lego bricks. Software allows to insert arbitrary unitary matrices specifying robot behaviors. Robot reacts with typical emotions as the reactions to touching or lighting his sensors.

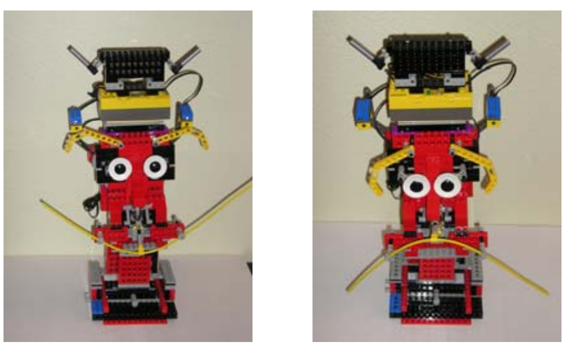


Fig 14. Mister Quantum Potato Head in the state of being Happy (left) and Sad (right). It is funny to watch him when he changes his emotions.

Old Duck Biped.

This robot walks with a grace of an old duck and uses only one brick. The plans are to add face with emotions to it (Fig. 20).

Fig 15. Kaczor or Old Duck biped

The evaluation ı implementing various robot controllers; deterministic, probabilistic and entangled on a robot and respective behaviors. The presented robot uses multiple-valued quantum logic-based automata. This includes reversible multiple-valued combinational circuits and automata as their special cases. When the circuit is reversible, the behavior of the robot is deterministic, but when a rotation angle of any Pauli rotation gate [7] in the (quantum) circuit is slightly changed, the behavior of the robot becomes probabilistic or even entangled. The user can thus partially control the level of “quantum-ness” of these behaviors by tuning certain parameters, which is an interesting exercise in understanding quantum algorithms and circuits.

6. Didactic Component of this Project

It is commonly accepted that “learning by doing” is the best way to educate scientists and engineers. This philosophy has been applied in Lego Mindstorms, Lego Dacta, and similar robotics toolkits. There are many textbooks that also attempt to teach elements of programming, physics, maths and electronics in a framework of Lego robot tasks and exercises. Portland State University Intelligent Robotics Laboratory found strong support from PSU administration, Intel Corporation and Portland and Beaverton School Districts to teach “high school robotics” based on these ideas since 1999.

In past educational projects with high-school students at the PSU IR Lab, such as Oregon’s Saturday Academy, we found that the concepts of deterministic Boolean logic as well as fuzzy logic could be taught to 16 to 18-year-olds and practically used in their software/hardware projects. In our graduate research, on the other hand, we found quantum logic to be interesting, as it relates to deterministic, probabilistic, and entangled sensor/actuator robot behavior mappings and thus covers a wide spectrum of behavioral possibilities. These projects were robot heads [12], stationary robot torsos, mobile robots and hexapod walkers [5,16], and a walking human-like biped.

Here, we follow the Lego builders’ philosophy but we take the next step; we present a new approach to teach middle school students about quantum computing. This was done in the framework of a 1-year project at the PSU Intelligent Robotics Laboratory. The students who worked on this project (12, 13 and 15 years old when started) are children of computer scientists, engineers, entrepreneurs, and university professors. They have been introduced very early on to robotics and mathematics, and they were focused, motivated and hardworking. This led to the didactic success of this project, including two awards such as the grand award at the 2006 Intel Northwest Science Expo for research involving multiple-valued transforms in quantum algorithms [17].

It should be pointed out that the project like this teaches many mathematics and computer science concepts like complex numbers, linear algebra, vector and vector spaces, matrices, classical logic and circuits, reversible circuits, finite state machines, quantum circuits and automata, probabilistic systems, quantum superposition, entanglement and parallelism, Heisenberg and Dirac notations, fuzzy logic, multiple-valued logic, goal-oriented and subsumption robot architectures. In our 1-year project, we had our weekly 2-hour meetings to discuss tasks, teach theory, and present robots (that were built and programmed at homes). All lectures are interactive and teens are called to the white board and solve problems related to the just introduced theoretical concepts. The students are constantly quizzed, challenged and tested for their understanding.

The goal of this paper is to share our success story and our findings so that they may motivate more groups like our in the future. We would gladly share our work with all interested robot builders who could easily reproduce our results and further advance these state-of-the-art “quantum robots.”

We continue our “quantum robotics for teenagers” with more students in year 2006/2007 and our projects include use of Matlab for calculations, evolutionary robot design [4], quantum transforms and their use in robot vision [17,18]. A video of our quantum controlled robots will be showed at the ISMVL conference.

7. Conclusion

The paper introduced the new concept of robots controlled by multiple-valued/fuzzy quantum circuits. We found that such circuits have higher potential to describe mixed deterministic/probabilistic/entangled behaviors of robots than classical robotic controllers. The user may investigate trade-offs between deterministic, probabilistic and entangled behaviors by tuning gates. The research goal of our laboratory is to investigate these concepts further, and the quantum emotional humanoid robots are already a subject of a Ph.D. Thesis [12].

We also believe that building robots with quantum brains is an excellent method to explain teenagers how a quantum computer works and teach them many related mathematical concepts that would be perhaps boring when taught without motivational application examples. A group of three teenagers from USA and Poland were able to build many quantumly controlled Lego robots and learn fundamentals of quantum computing in this process, and also contribute to a new research area that has been only very recently defined.

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