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# Possible Applications of Quantum Computing, Especially in Vehicle Technology: A Review Article

Ferenc Ignácz[1*], Dániel Feszty[2], István Lakatos[3]

[1] Department of Automotive and Railway Engineering, Faculty of Mechanical Engineering, Informatics and Electrical Engineering, Széchenyi István University, H-9026 Győr, Egyetem tér 1., Hungary
[2] Department of Whole Vehicle Development, Audi Hungaria Faculty of Automotive Engineering, Széchenyi István University, H-9026 Győr, Egyetem tér 1., Hungary
[3] Department of Automotive and Railway Engineering, Faculty of Mechanical Engineering, Informatics and Electrical Engineering, Széchenyi István University, H-9026 Győr, Egyetem tér 1, Hungary
[*] Corresponding author, e-mail: ignacz.ferenc@sze.hu

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**Abstract**
Given the current trend in the development of quantum computing, it can be expected that it will revolutionize many areas of science, including vehicle technology. In this review, we present the current research results of quantum computing technology and its possible application potential in the field of vehicle technology and structural simulation. In addition, we provide an overview of the current challenges, difficulties, and future of quantum computing.

**Keywords**
simulation, vehicle, automotive, quantum computing, high performance computing

## 1 Introduction

In vehicle development, FEA-based computational models will become increasingly complex, leading to a significant increase in simulation time. Structural optimization calculations with numerical simulation using classic (binary) computers are very time-consuming. On the other hand, certain computing tasks cannot be solved with classic computers or the solution is extremely time-consuming and has limited efficiency. One such problem is the simulation of a large number of atoms or molecules in material structure research. We need novel computational techniques and algorithms. There is a revolutionary new opportunity on the horizon, and that is quantum computing.

There are currently several experimental-phase quantum computing research programs underway to perform calculations on quantum computers, mostly in physical experimental laboratories. In the last few years, the practical application of quantum computers has already appeared in some areas, but there is still much to be done in this field.

Quantum computing represents a huge opportunity and application potential for industry, and at the same time it will significantly influence the development of many fields of science. More and more research institutes and companies (including Start-ups) are investing in this field, and the European Commission is also supporting this area with a significant amount (Möller and Vuik, 2017).

## 2 About quantum computing

Quantum computing belongs to the field of Quantum Information Science (QIS) (Hidary, 2019).

In the early 1980s, Richard Feynman drew attention to the fact that the physical world is quantum mechanical and that its simulation is not possible in an efficient way using classic computers since simulation of quantum systems is expensive or impossible using this approach. Simulation of the processes of nature is best done quantum mechanically, meaning with a quantum computer equipped with quantum mechanical elements (Feynman, 1982).

A quantum computer is essentially a physical device that utilizes the laws of quantum physics to perform computations (Lee et al., 2019). The laws of quantum physics are fundamentally different from the laws of classical physics, as well as real-life experiences. A very ideal problem for a

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quantum computer is the simulation of a quantum system, essentially a simulation of a quantum system with another quantum system.

Quantum computers are expected to perform certain computational tasks exponentially faster than the processors in binary classic computers can (Arute et al., 2019).

There are some important quantum mechanical phenomena that play a particularly important role in the speed of quantum calculations. One such important phenomenon is superposition, according to which a quantum system can be in two or more states simultaneously (Grumbling and Horowitz, 2019). Another important phenomenon is the entanglement: "The property where two or more quantum objects in a system are correlated, or intrinsically linked, such that measurement of one changes the possible measurement outcomes for another, regardless of how far apart the two objects are." (Grumbling and Horowitz, 2019:p.247–248).

## 3 Major milestones in quantum computing

Below is a list of key milestones in quantum computing (without claiming completeness).

- 1980: Paul Benioff presented the theoretical basis for quantum computing (Hidary, 2019).
- 1980: Yuri Manin formulated the core idea of quantum computing (Hidary, 2019).
- 1982: Richard Feynman suggested that a quantum computer would be able to solve problems in physics (Feynman, 1982).
- 1985: David Deutsch defined how a quantum computer would work (Deutsch, 1985).
- 1994: Peter Shor, a mathematician, developed his famous Shor's algorithm for integer factorization (Shor, 1994).
- 1996: Lov K. Grover published his algorithm for fast searching in unstructured databases with a quantum algorithm (Grover, 1996).
- 2011: "the World's first commercially available quantum computer" (annealer): D-Wave One 128 qubit (Tanaka et al., 2017:p.274).
- 2014: Threshold for fault tolerance, achieved (superconducting quantum circuits) (Barends et al., 2014).
- 2016: The IBM Q Experience released: cloud-based platform with general public access.
- 2019: World's first integrated universal approximate gate-based quantum computer system for commercial use (IBM, 2020).
- 2019: Quantum supremacy, achieved by Google (Arute et al., 2019).

## 4 The quantum computing principle compared to the classic method

Classic digital computers store the data in the various states in bits (Möller and Vuik, 2017):

$$b \in \{0,1\}.$$

A 1-bit register can take one state at the same time. Based on the analogy of a switch, the on state corresponds to "1" and the off state to "0" as shown by Fig. 1.

For a system that can assume one of two different discrete states, we can represent these two states in Dirac notation (Hidary, 2019) as follows (Abhijith et al., 2020):

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix},$$

and

$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}.$$

The functional principles of a Quantum Processor Unit (QPU) are based on the laws of quantum mechanics (Britt and Humble, 2017). The Quantum Processor Unit of quantum machines "(…) stores computational states in the form of a quantum mechanical state." (Britt and Humble, 2017:p.3).

In terms of superposition, the quantum bit takes a linear combination of states as follows in Eq. (1) (Nielsen and Chuang, 2010):

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad (1)$$

where $\alpha$ and $\beta$ are complex numbers $(\alpha, \beta \in \mathrm{C})$ and the following rule applies in Eq. (2) (Nielsen and Chuang, 2010):

$$|\alpha|^2 + |\beta|^2 = 1. \quad (2)$$

The "(…) quantum state is formally defined as a unit vector in finite-dimensional Hilbert space." (Britt and Humble, 2017:p.3).

A quantum bit (or qubit) can point in any direction on the spherical surface (Fig. 2).

With the addition of each qubit, the computational power is doubled.

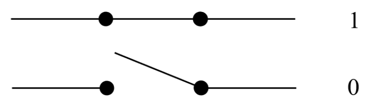


**Fig. 1** The representation of classic bit
(Source: Drawn by the authors)

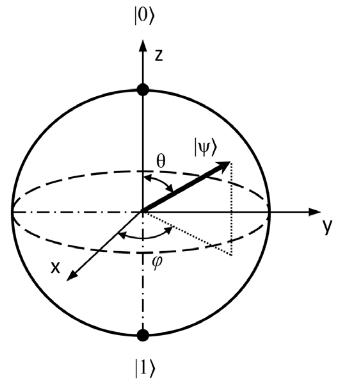


**Fig. 2** The Bloch sphere representation of quantum bit (qubit) (Source: Drawn by the authors, based on the FIGURE 2.3.1 in (Grumbling and Horowitz, 2019))

Quantum computers are significantly more prone to errors than classic (binary) computers.

## 5 Gate-based quantum computers and quantum annealers

The gate-based quantum computers developed by IBM, Google, Rigetti, Intel, etc. are eventually suitable for running algorithms such as the Grover's algorithm, however they are sensitive to decoherence and after the measurement the wave function collapses.

The control of the qubits and the readout of the calculation results mostly happen with the use of laser pulses or microwaves (Grumbling and Horowitz, 2019).

In 2018, the two most commonly used technologies for quantum computers were artificial atoms and trapped ions (Grumbling and Horowitz, 2019).

The IBM Quantum Experience (IBMQX), a cloud-based, general access quantum computing platform (released in 2016 with 5 qubits) is available to everyone after registration on a cloud basis. Since May 2018, there are now 3 processors: 2 × 5-qubits processor and 1 × 16-qubits processor (Fig. 3, Caleffi et al., 2018). The system is suitable for gate-based quantum computing.

The user interface of the quantum computer is in the form of diagrams representing single- and two-qubit gates (Lee et al., 2019).

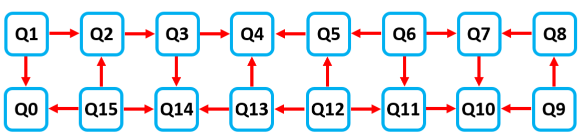


**Fig. 3** Coupling map of the IBM 16-qubit quantum machine, IBMQX5 (Source: Drawn by the authors, based on the Figure 3: in (Caleffi et al., 2018))

The IBMQX quantum system can be programmed with the quantum computing dev library Qiskit (Quantum Information Science Kit) developed by IBM and released in 2017 (Hidary, 2019).

Quantum annealing is particularly well suited for combinatorial optimization problems (Kobayashi, 2020).

## 6 About quantum supremacy

The definition of Quantum Supremacy originally comes from Caltech professor John Preskill (Hidary, 2019): "(…) we will be able to perform tasks with controlled quantum systems going beyond what can be achieved with ordinary digital computers." (Preskill, 2012:p.2).

Google engineers claim to have achieved the so-called Quantum Supremacy in 2019, which essentially means that a strictly theoretical, special calculation that could not otherwise be used in practice could be performed on a quantum computer, being orders of magnitude faster than the time a state-of-art classic supercomputer would need. The Nature paper (Arute et al., 2019) presents Google's quantum processor with programmable superconducting qubits, that can generate quantum states on 53 qubits. This essentially corresponds to a computational state-space of dimension $2^{53}$ (about $10^{16}$). According to the paper the Sycamore processor can perform a certain operation in 200 s, which would take 10,000 years for today's state-of-the-art classic computers, which represents such a large increase in computing speed over the classic computer that it is essentially an experimental realization of Quantum Supremacy. This is seen as a major milestone on the road to full-scale quantum computing (Arute et al., 2019).

The system includes 53 working qubits and 86 connecting parts.

To show the Quantum Supremacy, they compared the "(…) quantum processor against state-of-the-art classical computers in the task of sampling the output of a pseudo-random quantum circuit." (Arute et al., 2019:p.506).

It was verified that the quantum processor works correct, using the so-called cross-entropy benchmarking. The state of qubits can be read in real time, for which the so-called frequency multiplexing technique is used (Arute et al., 2019).

According to the article's authors the quantum error correction must be the focus of attention. This is necessary to sustain the double-exponential growth rate, as well as the well-known quantum algorithms such as the Shor or Grover algorithm eventually can be runned (Arute et al., 2019).

## 7 Integration of quantum processors into High Performance Computing systems

High Performance Computing (HPC) systems are of immense importance in the automotive industry, just think of the extremely resource-intensive Computer Aided Engineering (CAE) applications. According to the current state of science, the integration of Quantum Processor Units (QPU) into modern High Performance Computing systems will be a complex challenge.

Britt and Humble (2017) describes two ways to do this. HPCs need to ensure efficient interoperability of classic binary and QPU processors, which assumes essential parallel computations. Resolution of computational domains is a typical case of parallel computations. Although data exchange between individual computational models is theoretically possible, ensuring stability is a difficult task.

## 8 Quantum algorithms and the numerical methods

Montanaro and Pallister (2016) investigated to what extent the Finite Element Method (FEM) can be accelerated using an efficient quantum algorithm. They found that the QLE (Quantum Linear Equation) algorithm is actually applicable to the general FEM and can achieve considerable accelerations compared to the classic algorithm. Nevertheless, the quantum speedup is at most polynomial in a certain case.

They showed that if you compare quantum and classic algorithms for FEM, fairly considering all aspect of the problem, an obvious exponential quantum advantage can sometimes disappear (Montanaro and Pallister, 2016).

Harrow, Hassidim and Lloyd developed and presented the first quantum algorithm (HHL algorithm) which is suitable for solving a linear system of equations with sparse matrices (Möller and Vuik, 2017).

In March 2019, a scientific report (Lee et al., 2019) was published describing a hybrid quantum algorithm (modified version of the HHL) developed for solving systems of linear equations. The algorithm was tested on an IBM Quantum Experience, namely a 5-qubits quantum computer. Based on the calculations, it was proved that the newly developed algorithm provided higher accuracy on specific system of linear equations than the HHL algorithm.

It is important to highlight the statement in the article that quantum algorithms have been developed in recent period assume so-called noise-free quantum computers.

In contrast, current quantum computers are still relatively noisy in practice and thus algorithms cannot yet be run efficiently.

It is an interesting fact that the Shor's algorithm, developed by the American mathematician Peter Shor, has been in existence for more than two decades since it was developed by the scientist in 1994. This algorithm (Shor, 1994) is used for prime factorization of integers. Today's encryption algorithms (e.g., RSA) are also based on the prime factorization of integers, which for large numbers is such a complex task for even a classic binary computer that the solution cannot be done in the foreseeable future (Caleffi et al., 2018). However, as the performance of quantum computers increases, it is likely that over the next 10–15 years, it will be possible to a build a quantum computer that will be able to break public-key cryptography schemes. Accordingly, with the advent of quantum computers, data security professionals need to develop new types of encryption procedures.

Lov K. Grover developed a fast algorithm for searching in unstructured databases with quantum algorithm. This algorithm enables the search in only $O(\sqrt{N})$ steps (Grover, 1996). This quantum algorithm takes the advantage of the phenomenon of quantum mechanics that quantum mechanical systems can be in superposition, thus allowing simultaneous search for multiple values.

It is important to highlight that the development of quantum algorithms is also supported by quantum simulators. Quantum algorithms can also be tested on quantum simulators, which are an integral part of today's quantum development platforms (Hidary, 2019).

## 9 Challenges and future of quantum computing

It is important to mention that the development, manufacture and maintenance of quantum computers pose enormous challenges to professionals and require specialized expertise (Möller and Vuik, 2017).

The quantum processors need an extreme environment shielded from vibration and electromagnetic field to function properly. Either they are cooled to nearly absolute zero (10–20 mK) or are located in vacuum (or both) (Grumbling and Horowitz, 2019). That is why most of the quantum computers are in data centers and users can access them via cloud (Möller and Vuik, 2017). However, thanks to the continuous, intensive development of quantum computers, progress has already been made in this area. IBM introduced the world's first circuit-based integrated commercial quantum computer in January 2019 (Fig. 4).

The programming of quantum computers requires fundamentally and completely different ways of thinking and different knowledge. This essentially means that programmers who program quantum computers need to be specially trained for this task.

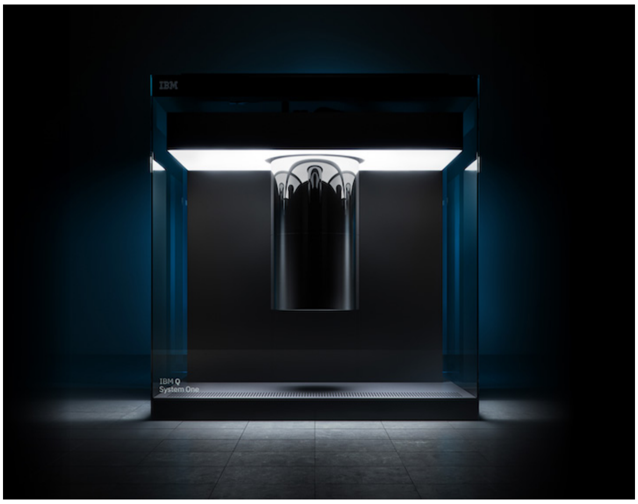

**Fig. 4** The IBM Q System One Q, Copyright: IBM (IBM, 2020)

Nowadays, quantum computers are moving step by step from physical laboratories to industrial, practical use (Yarkoni et al., 2019).

Unfortunately, the quantum computers existing nowadays are not error-free, and the error correction is an exceedingly difficult task, it could even be seen as still being in its infancy.

Today, we live in the age of so-called NISQ (noisy intermediate-scale quantum). This term was defined by John Preskill (Hidary, 2019).

One of the biggest challenges in quantum computing is the efficient error correction (Möller and Vuik, 2017).

According to the no-cloning principle, it is not possible to create a perfect copy of a qubit without ruining the superposition state of the source. In essence, this also means that classic error correction procedures (e.g. repetition codes) cannot be applied to quantum computing and other specialized quantum correction procedures (e.g. surface codes) are required (Möller and Vuik, 2017).

It is estimated that quantum computers with an acceptably low error rate can be expected to appear within 4–15 years.

## 10 Possible areas of application of quantum computing, especially in automotive

Quantum computers in the field of automotive technology – which is relevant to our research field – can be used for the following purposes as expected.

### 10.1 Material structure research in vehicle technology using quantum computing

Although quantum computers currently are relatively noisy and full quantum error correction does not exist yet (Rice et al., 2020), they can already be used for certain tasks, such as material structure research.

The material research does not require the quantum computer to have full error correction. Thus, we can already experience the practical usability of quantum computers in this field. Research in this direction has already begun and will gain more and more ground in the near future.

Although electric car batteries have an increasing capacity thanks to continuous developments, there is still much to be done in this area, as the range of electric cars is still relatively short.

IBM and Daimler is working to develop lithium-sulfur batteries, which could be the next generation of battery technology (theoretical capacity of up to 1675 mAh/g) (Rice et al., 2020).

According to the authors of the article, they were the first ever to perform the calculation of dipole moment on quantum hardware. The IBM Q Valencia 5-qubits quantum computer was used for this calculation (Garcia, 2020).

To achieve the research goals, the Schrödinger equation for the affected molecules must be solved, which is exponentially expensive with classic, binary computers (without approximation schemes) (Rice et al., 2020).

The open source Qiskit programming language was used for programming. The "Aqua" module of Qiskit contains the implementation of the hybrid (quantum-classical) VQE algorithm to solve the Schrödinger equation (Rice et al., 2020).

The qualitative behavior of both dipoles (Fig. 5) and energies is correctly recorded upon extrapolation by the hardware simulations (Rice et al., 2020).

In order to make sure the calculations were correct, they were also run on a classic computer, namely using the IBM quantum simulator. Based on the calculations performed on the classic computer, it was found that

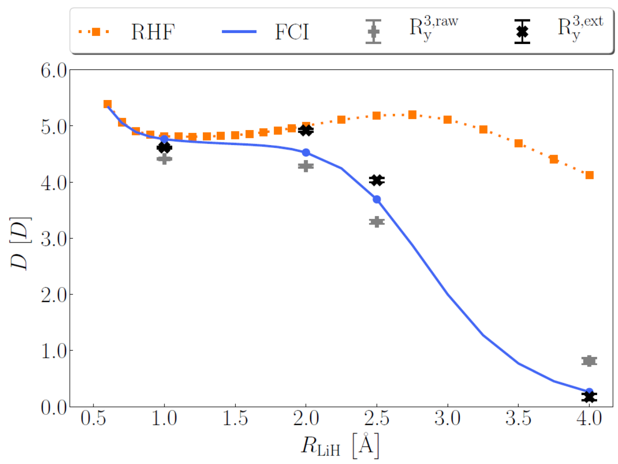


**Fig. 5** "Hardware-simulated dipole moment calculations for LiH on the IBM Q Valencia device (dipole moment in Debye, as a function of interatomic distance, in angstroms). D denotes Debye" (Source: (Rice et al., 2020:p.4))

despite the noisy qubits, sufficiently accurate results were obtained (Garcia, 2020).

### 10.2 Structural optimization

Quantum computers are envisaged to be able to solve linear systems of equations quickly and efficiently. It is expected that this will allow the development of fast and efficient structural optimization algorithms for structural optimization of automotive structures.

For example, optimization of car parts using quantum computer is also a topic at Volkswagen (Yarkoni et al., 2019).

A new algorithm would enable automotive optimization to be carried out in a significantly shorter time. The economic advantage of this is that the product development cycle time could be shortened significantly and therefore the development costs of new vehicles could be crucially reduced.

### 10.3 Route optimization

Quantum machines are also efficient in optimization tasks and further efficiency gains are expected, so much more accurate and efficient traffic-flow optimization systems can be developed. Such a system already exists, developed by the Volkswagen Group (Neukart et al., 2017) using the Canadian D-Wave quantum computer for its calculations.

### 10.4 Data encryption

As self-driving vehicles are planned to be able to communicate with each other, it will be necessary to protect and encrypt the flow of information, which will also be possible with the help of quantum technology (cryptography).

### 10.5 Autonomous driving

Quantum computers will be suitable for use in the fields of machine learning, artificial intelligence, and data mining, so that efficient self-driving systems can be developed (Yarkoni et al., 2019).

### 10.6 Control of automated guided vehicles in automotive

We would also mention here the optimizing of plant processes by quantum annealer (a kind of quantum computer), which was carried out by the Japanese company Denso through optimized controlling and automatically running large number of factory vehicles without collision (Ohzeki et al., 2019).

## 11 Conclusions

Research activities on quantum applications for automotive are indeed multidisciplinary including sciences like quantum physics, automotive engineering, computer science and mathematics.

Nowadays, quantum computing is increasingly moving from physical laboratories to real applications. There are many opportunities to succeed in developing a quantum computer with small errors that can be used in real-world applications. Many manufacturers are working intensively on this, however, it is estimated that the real breakthrough could be achieved in the next 5–15 years.

By quantum computer based research of the structure of molecules and atoms, new materials for automotive and more efficient automotive batteries can be developed, thus increasing the range of electric vehicles and making batteries smaller.

Since the quantum computer is also suitable for solving linear systems of equations and partial differential equations, in our opinion it is possible to develop an algorithm suitable for finite element-based structural optimization that can be used even in automotive structural optimization in new car development.

The algorithm to be developed could be widely used in automotive development where short product development cycle times are required.

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