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Quantum information technology: introduction and current state of research

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ABSTRACT

While quantum technologies have made great progress in recent years, several fundamental challenges remain unsolved today. At the same time, the benefit in case of a successful realization of quantum technologies for practical problems is expected to lead to major disruptions in many application domains. In this perspective paper, we first outline the principles underlying quantum information technology. Then, we describe specific application domains relevant to industry where quantum computing, quantum sensing, and quantum communication could be successfully employed. Finally, we briefly introduce the research topics currently investigated at the Honda Research Institutes which should prepare a successful application of quantum technologies on realistic applications in the future.

1. Motivation

The field of quantum information technology is currently witnessing breakthrough moments. Various quantum computing hardware systems have been realized and many of such systems have matured to be accessible via web-based services, notably from IBM, D-Wave, or IonQ. While these systems are primarily used for scientific proof of concept applications, there are first experiments on quantum hardware claiming to have breached the barrier to a quantum advantage[1), 2)].

It is commonly recognized that quantum technologies have a highly disruptive potential in many application domains. Shor's algorithm[3)] for factoring numbers is the archetypal example, where an exponential speed-up over the best-known classical algorithms could be realized, and which would lead to a breakdown of classical public key encryption schemes like RSA. Another example is Grover's search in unstructured databases[4)], which offers quadratic speedup. However, both algorithms require fault-tolerant and error-corrected hardware devices with millions of qubits, which cannot be realized in hardware today.

The current quantum computer hardware devices are of the so-called "noisy intermediate-scale quantum" (NISQ) [5), 6)] type, and face a number of serious obstacles: They (a) realize only a limited number of qubits (100-1000), which restricts the attainable problem sizes, (b) suffer from noise and errors that are often poorly understood, (c) lack mechanism of error-correction and thus are unable to demonstrate useful complex quantum algorithms beyond proofs of principles, (d) allow only for limited flexibility and control to non-specialist end-users, and (e) are not certified in an assumption-free manner, which means that they are not experimentally verified to operate in a fully quantum regime with all the properties which in theory they should have.

The fundamental building blocks of quantum computers are quantum bits called qubits. Their realization in hardware is based on many different types of physical systems, notably two-level spin systems, trapped ions, photons, or superconducting flux qubits. These quantum devices have also become building blocks for quantum sensing, where quantum properties and specific quantum phenomena are used to precisely measure physical quantities. Quantum devices are very sensitive to environmental changes. While this is a major obstacle for quantum computing, for quantum sensing it enables unprecedented sensitivities and precision[7)].

The combination of high risk and high potential makes the field of quantum information technology very attractive for many different players. A huge amount of venture capital is funding many startup companies,

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traditional industry players are investing heavily (e.g., Quantum Economic Development Consortium (QED-C) [8] or Quantum Technology and Application Consortium[9]), and government initiatives are launched with an estimated investment of US$25 billion in 2021[10].

There are realistic short- to midterm opportunities for quantum technology to provide a benefit for certain applications. However, the identification of industrially relevant problems with significant benefits and the timing remains unclear. At the same time, there is no shortage of scientific roadmaps that formulate strategic research directions[11), (12)].

We need to be aware that the recent disruptive advances in AI demonstrated with large generative models such as the large language models GPT and BERT or text-to-image models like DALL-E or Stable Diffusion have only been possible with respective advances in the computing capabilities like GPUs. Even though it will not happen in the short term, quantum computing has the potential to exponentially speed up the training of next generation AI models. This could allow online training of very large generative models.

For the foreseeable future, quantum computing will not be "off-the-shelf". The successful application of quantum information technology will require experts, and it is necessary for most large companies to establish in-house expertise to be ready to exploit quantum information technology and to be able to correctly judge the state of research and the quality of potential partners.

The high risk involved mandates to maintain an informed and austere position when evaluating the state of the art and what we might expect in the next years.

In the following sections, we want to strike a good balance between showing that quantum technologies will become practically relevant in the mid-to-long term while not concealing that currently the technology faces many unsolved issues in the hardware and the software domain. At the Honda Research Institutes (HRIs) we want to facilitate the discussion in Honda on quantum information technology and encourage the assembly of the necessary expertise to exploit its exciting potential early, efficiently, and decisively.

2. From Quantum Physics to Quantum Technology

2.1. Introductory remarks on quantum physics and quantum information technology

The principles and laws of quantum physics were conceived to correctly describe, interpret, and predict several famous experiments that could not be explained by classical physics. The abnormalities that we find in the laws of quantum physics are a result of the strangeness of the experimental observations. Quantum physics describes phenomena in the microscopic world of atoms and elementary particles, which are often counterintuitive to what we observe in the macroscopic world. The measurement process in a physical experiment connects the microscopic to the macroscopic world and it is one of the central aspects both in quantum mechanics as well as in quantum information technology. There is no clear differentiation between classical and quantum worlds and recent physical experiments with large molecules[13] show that quantum phenomena are not restricted to the smallest of particles only.

Major fundamental principles of quantum physics are:

1. quantum mechanical systems and particles are described by a state vector also called wave function, which describes in which of all possible states the system can be found;
2. there exists an inherent uncertainty in values attributed concurrently to some physical variables like position and momentum of a particle;
3. quantum states of particles have additional (microscopic) properties, which have their own governing rules and conservation laws.

The state vector is typically a superposition of different states that the particle can be in. Therefore, the first principle of is often also referred to as the superposition principle. Particularly, the first two principles imply that in the microscopic world there is an inherent and irreducible uncertainty, and any description needs to be based on probabilities. The probabilistic nature of the microscopic world can only be partially removed with a macroscopic measurement.

An example of a purely quantum mechanical property of the third principle is the so-called spin of a particle. Technically, the spin is an intrinsic angular momentum, however, it is better to avoid the classical interpretations of this as something rotating in the microscopic world. The total spin is conserved when particles interact. That is, the total spins of all particles before an interaction must be the same as after an interaction. This is true regardless of how far apart the particles are separated after the interaction. This leads to a phenomenon called "entanglement" where two (or more) quantum systems which are spatially separated still need to fulfill a joint governing rule. As a direct consequence, if one of the entangled particles is measured and a certain spin value is observed, this immediately implies a specific value for the spin of the other particle. This non-local nature of entanglement has spurred great controversy and has led Einstein and others to believe that quantum mechanics can only be an incomplete description of reality since such "spooky action at a distance"[14] cannot be real. However, the very strange quantum nature of reality has been confirmed in many experiments by now and seminal experiments were awarded the Nobel Prize in Physics in 2022[15]. Also, it is exactly these three principles and the resulting entanglement property that are the building blocks of the (potentially) unique capabilities of quantum computers, quantum sensing and quantum communication.

The basic units of information in a classical computer

are the two binary states "{1}" and "{0}" called bits. In a quantum computer these two states are replaced by quantum bits called qubits. The probabilistic nature of the microscopic world implies that the qubits can be a mixture of different states: just like in the spin example, they are with a certain probability concurrently in state "{0}" and "{1}". This superposition principle combined with the entanglement property of quantum physics, leads to a new type of parallel computing that we briefly elucidate and compare to classical parallel computing in the next section. Isolating quantum systems from the surrounding environment so that they maintain quantum properties, typically called quantum coherence, is technically demanding. While this poses a major challenge for quantum computing applications, it is positively exploited in the field of quantum sensing. There, measurement devices are devised that have very high sensitivity to environmental influences and thus allow for unprecedented sensitivities for measuring physical quantities like magnetic fields. Similarly, quantum communication relies on the fact that spatially separated quantum systems can maintain their quantum coherence even over long distances and thus allow for detecting unauthorized eavesdropping. This enables the implementation of highly secure communication channels.

2.2. Quantum simulation: simulating quantum systems with quantum systems

The simulation of quantum mechanical systems on classical computers is computational costly and cumbersome. This was the reason for Feynman and Benioff to propose the concept of quantum computers where such simulations would be much more efficient[16), 17)]. Since then, the field of quantum simulation has evolved substantially, and several realistic quantum effects have been computed on actual quantum hardware[18)].

Currently, these simulations are on a rather fundamental level, elucidating basic scientific questions. However, it is conceivable to simulate industry-relevant processes or materials on larger quantum computers or quantum simulators for e.g., battery design.

2.3. Quantum computing: from classical bits to quantum bits

We have already mentioned that in quantum computing the bits of classical computing are replaced by qubits and in Table 1 we have summarized the significant differences.

It is interesting to consider the differences between parallel computing in a classical high-performance computer and intrinsic parallel computing in the quantum computer, which is sketched in Fig. 1. The performance gain of both relies on parallel computing, however, the way the parallelization works is profoundly different. In the classical parallel computer, a task is divided into suitable subtasks, which are executed in parallel on different physical processing units. The main task is to develop an algorithm that divides a problem into subproblems that can

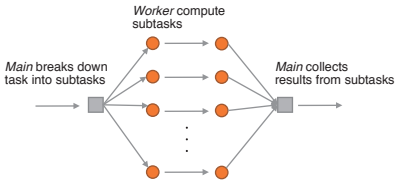
Table 1 Comparison of classical bits and quantum bits

Classical bit	Qubit
State is either {0} or {1}	Superposition of different states: "α·{0}+β·{1}"
Read-out is deterministic	Read-out is probabilistic
Read-out does not affect the state	Read-out changes the state of the qubits
	Multiple qubits can be entangled

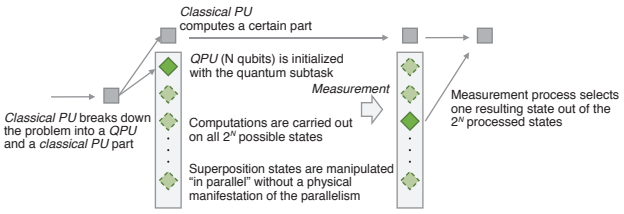
be processed in parallel with efficient information exchange between the subprocesses and whose solutions can finally be combined to the solution of the original problem.

In the quantum computer, N qubits can occupy each of the possible 2^N states at the same time with a certain probability. This is a consequence of principle 1 – the superposition principle. But such a superposition of all possible states is still just one quantum state. Applying one quantum operation to this one state inherently results in an operation on all states in the superposition. Therefore, 2^N states can be manipulated by applying one operation to a N-qubit system. This is usually referred to as quantum parallelism: without explicit physical realization, 2^N states can be processed at once, which is in weird contrast to our daily experiences. However, the naïve exponential speed-up of processing 2^N states with just one operation in parallel has a catch and cannot be directly realized in practice. Reading out the results requires measuring the quantum state, and a measurement only returns one of the possible 2^N states as a result. Therefore, one would need on the order of 2^N measurements to get out all results, which directly spoils the quantum advantage.

Therefore, the art of solving a practical problem with the help of a quantum computer is to formulate an algorithm that makes smart use of the superposition property. The results of the 2^N calculations need to be utilized in such



(a) Classical parallel computing (basis for high performance computers or GPUs)



(b) Parallel computing in a quantum computer

Fig. 1 Schematic representation of classical and quantum parallel computing

a way that it produces a state where the solution to the original problem can be extracted directly. This is a complex endeavor, and only a few algorithms have been proposed for specific problems like e.g., factorizing large numbers (Shor's algorithm[3]), finding needles in a haystack (Grover's search[4]), or solving sparse linear algebra systems (Harrow-Hassidim-Lloyd (HHL) algorithm[19]).

However, these types of algorithms are currently far out of reach to be run on actual quantum hardware. They require thousands of perfect qubits and quantum gate operations, which have very low error rates, and which can maintain quantum properties (coherence and entanglement) for long times and over large number of elementary quantum operations.

In contrast, current NISQ devices encompass only up to few hundred qubits with rather short coherence times and large gate errors. Full error correction schemes, where multiple physical qubits are utilized to mitigate errors and to encode one logical qubit are believed to require a factor of at least 1000 times more physical qubits. Such an increase in the scale of the number of qubits is currently not within reach for the foreseeable future.

Therefore, most current research on quantum computing focusses on how to utilize the current NISQ devices efficiently. Various hybrid quantum-classical algorithms have been proposed, where the quantum device consists of quantum gates, which have freely tunable parameters (see Figure 2). This parametrized quantum circuit produces a final quantum state, which depends on these parameter values, and which is set up to encode the solutions to a predefined application problem. The best possible solution is then obtained by employing a classical optimization routine to determine the optimal values of the parametrized quantum circuit. Such variational algorithms have been successfully used in many proof of principle applications such as quantum chemistry, quantum machine learning, or combinatorial optimization problems[5], [6], [9], [20], [21].

Besides their application to NISQ devices, the proposed

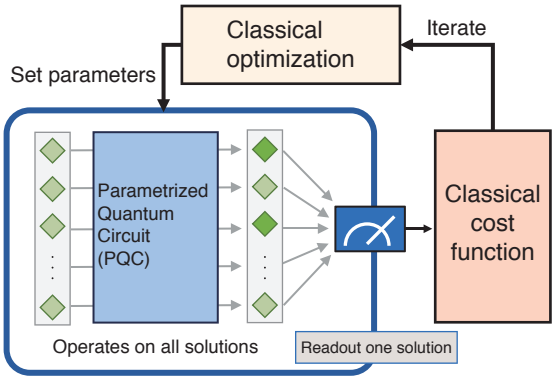


Fig. 2 Schematic representation of a typical hybrid quantum-classical approach on NISQ devices where the parameters of a quantum circuit are determined by classical optimization.

algorithms are expected to be highly beneficial for future fully error corrected fault tolerant quantum devices as well. It is generally believed that quantum computing will not replace classical computing, but both techniques will coexist and will be complementary. There will be applications where classical computing is and always will be more effective than quantum computing, but there will also be specific application scenarios where quantum computation will be favorable. And most likely for many applications these hybrid quantum-classical approaches developed today in the NISQ era will be efficient approaches as these can leverage the best of both worlds.

2.4. Quantum sensing: exploiting quantum phenomena for new high-precision devices

It is expected that quantum sensors can surpass the sensitivity of classical technology for practical applications in the near term. They promise to provide unprecedented sensitivity for the measurement of physical quantities like electric and magnetic fields, rotations and acceleration, pressure and strain, frequency, and time. Quantum sensors exploit quantum phenomena and their very high sensitivity to external influences to achieve high precision measurements.

Quantum sensing devices typically rely on utilizing one or more of the following characteristics of quantum systems. (a) the discrete energy levels of small quantum objects, (b) quantum coherence and superposition of quantum states, and (c) quantum entanglement, of which the latter two are very sensitive to environmental disturbances. To ensure proper functioning as a quantum sensor[7], additional requirements need to be fulfilled:

1. these devices need to allow that their energy levels can be measured,
2. the sensor devices need to be initialized into a well-defined state,
3. the operator needs to be able to manipulate the sensor coherently by, e.g., time-dependent fields,
4. the sensor must interact with the physical quantity to be measured such that changes in the quantity produce a change of the quantum system's energy levels.

The sensitivity η of a network of N quantum sensors can be shown to scale like $\eta \propto 1/(\gamma (NT)^{1/2})$, where γ is the strength of the interaction mentioned in the above requirement 4. and T is the coherence time. This scaling behavior is called the standard quantum limit (SQL), which is an improvement over the sensing limit of a single device by a factor of $1/N^{1/2}$. Recently, it has been proposed[22] that the scaling can even surpass the SQL when states of the sensor network are entangled. In that case, the sensitivity increases by another factor of $1/N^{1/2}$.

2.5. Quantum communication: towards unbreakable security

The field of quantum communication is already quite

advanced and mature[23]. The main value of quantum communications is its security. Instead of qubits, the quantum states of light, so-called photons, are used to transmit information between two parties. It takes advantage of quantum entanglement between two or more photons to protect the information from undesired interceptions. The information can only be recovered by measuring the photons, which unavoidably changes the photons. Therefore, anyone trying to eavesdrop must also measure these photons, which then leaves a detectable trace. The major challenge of the field of quantum communication is the design of efficient ways to encode data into quantum communication channels.

The major application considered today is the so-called quantum key distribution (QKD). The goal is to create a shared secret key between two parties that is perfectly secure. This shared key is used to generate private keys which are then used to encrypt and decrypt communication messages between the two parties using classical encryption methods.

Secure quantum communication can also be used to build quantum networks to transmit digital information, e.g., for banking, medicine, navigation, or transportation applications. Quantum networks have not been practically realized yet and there remain many technical challenges[24], however, their impact would be substantial.

3. Impact of quantum technology for selected applications

3.1. The case for quantum computing technologies

The application domain with realistic industry-scale use cases, where quantum technologies can demonstrate a significant advantage, has not yet been identified. To date most success-cases have either been confined to simplified benchmark problems or have been theoretical (like Shor's algorithm).

However, if some technical challenges can be overcome there are application domains, where benefits can be expected even in the short to midterm. In the long-term, when fully error corrected quantum computing hardware with very high number of qubits will be available, the impact will be enormous.

Applied quantum chemistry and material science are industrial application domains of high relevance. Simulating and understanding the chemistry and dynamics of the materials in batteries, particularly the lithium chemistry of cathode materials, is crucial for the development of novel and better batteries. Simulating quantum processes and properties of molecules and compounds on a quantum computer is much more efficient than doing it on classical computers. Similarly, the search for better catalyst materials to enhance the efficiency of fuel cells is also a field with large potential for quantum computers.

Most engineering design processes employ simulations of flow dynamics and of static and dynamic stability of components using finite-element methods and sparse linear systems to solve partial differential equations. These simulations are computationally very demanding and current computational restrictions limit prediction accuracy and complexity of components and systems that can be simulated. It has been shown[25, 26] that physical simulations can substantially benefit from fault tolerant quantum computers leading to enhancements of a variety of industrial products.

Combinatorial optimization problems, such as scheduling optimization or assignment problems frequently occur in electromobility services, manufacturing and supply chain logistics. They are equally likely to substantially benefit from fault tolerant quantum computers. Indeed, combinatorial optimization problems are among those that also benefit from annealing type quantum computers, which are currently available and which we reviewed in Ref.[27].

The utilization of quantum computing for data driven machine learning tasks is pursued in the very active field of quantum machine learning[28]. Several algorithms have been proposed which reduce the computational time to train quantum machine learning models. Additionally, and probably more importantly, many quantum machine learning algorithms are expected to need less training data samples to achieve good performance. This will reduce the barrier for deploying quantum machine learning models in realistic application scenarios substantially. Areas which can benefit a lot are quality assurance by automatically analyzing ultrasonic test data from manufactured parts, online monitoring of process data from large manufacturing plants, fault and anomaly detection for complex engineering systems or logistics applications. It is expected that quantum machine learning can thus lead to much more efficient utilization of sparse realistic data in various domains.

Specialized hybrid quantum-classical algorithms are being developed for the currently available NISQ devices for which the following near to mid-term benefits can be expected: in hybrid quantum optimization routines, the possibility to generate quantum states that contain exponentially many classical solutions in superposition leads to a more efficient exploration of the vast search space of combinatorial optimization problems. As a result, more solution candidates can be evaluated and tested during the search. This would lead to more efficient optimization approaches and higher quality solutions. If the algorithms are designed properly, the final states of such quantum optimization algorithms should be able to encode many similarly good solutions of the given problem at the same time. This would provide multiple, structurally different options all of equal quality to the decision makers.

Approaching very complex realistic problems on NISQ quantum computers will not be possible due to the limited number of qubits in such devices. However, quantum approaches can provide a benefit in such cases as well, as they can be used to efficiently find many solutions to simplified problems. These can then be used as

initializations for classical algorithms applied to the original complex problem.

3.2. The cases for quantum sensing

Quantum sensors can be realized for a variety of applications, such as gravimeters, interferometers and magnetometers, to name a few. The advantage of exploiting quantum phenomena is particularly notable for magnetometers. These devices use the spin of electrons or atomic nuclei to measure a magnetic field. Superconducting quantum interference device (SQUID) sensors exploit superconductivity to measure very small electric currents induced by magnetic fields. SQUID sensors are widely deployed in applications since decades due to their high sensitivity. However, superconductivity requires extremely low temperatures which makes SQUID sensors difficult to handle. Recently proposed alternative quantum magnetometers use nitrogen-vacancy (NV) centers, which will be discussed in Section 4.4.

Highly sensitive magnetometers have several unique and interesting applications, e.g., in-vivo monitoring of structural health of batteries, wearable sensors for magnetoencephalography (brain activity detection) or satellite-free indoor/outdoor navigation by using the earth magnetic field.

4. Research focus of Honda Research Institutes

The Honda Research Institutes (HRIs) are currently assessing the current state of the art in quantum technologies and are evaluating their potential future impact. One key challenge is to understand the current capabilities and limitations of quantum technologies as well as to develop concise and well-founded expectation of how these technologies will develop in the near- and mid-term future. One prerequisite is to advance our own experience and thereby expertise and assemble a network of partners from university and companies.

4.1. Electric vehicle scheduling and charging applications

The optimal management of electromobility services plays an important role in achieving zero emission targets. On the one hand, to be sustainable green energy sources should be used as much as possible and on the other hand, customer needs have to be satisfied, and revenue generated.

A directly related technical problem is the optimal operation of a large fleet of electric vehicles (EVs). EVs need to be scheduled to fulfill customer requests for trips for which the state of charge of the battery must be sufficient. Since electricity cost varies substantially over time, the operator can save cost by optimizing the charging schedule of the EVs. Additionally, large operators may have access to on-site generation of renewable energy e.g., using photo-voltaic (PV) systems, which could be used to reduce cost, contribute to stabilizing the grid by balancing the demand or increase independence of the electricity grid. A schematic overview of the various components of such a service is shown in Fig. 3.

Apart from these targets for the mobility service, there exist several technical and operational constraints that need to be fulfilled, e.g., for each time slot only one EV can be assigned to one charging station.

Although the electric vehicle scheduling problem is in principle well suited for quantum computing, its realistic set-up is more challenging:

1. The realistic problem formulation has many constraints, and especially inequality constraints are difficult to handle with a quantum computer.
2. The real operational environment will differ from the simulations used for the optimization. Therefore, the solutions must be sufficiently robust to cope with these variations. Robust optimization techniques are currently not available for quantum computers.
3. The operation of a service should achieve many different, often even conflicting objectives. The solution to such a multi-objective optimization problem is a set of Pareto-optimal solutions, where each solution represents an optimal trade-off between the objectives. Current quantum optimization approaches can only handle single objective problems.

All these three issues are addressed in current research projects at HRI in the context of electro-mobility service applications.

We have investigated a simplified but still realistic EV charging problem where the task was to find a valid assignment of several EVs to different charging stations while minimizing some additional cost function[29]. The problem can be formulated as a max-*k*-graph coloring problem with an additional cost function, see Fig. 4(a). We

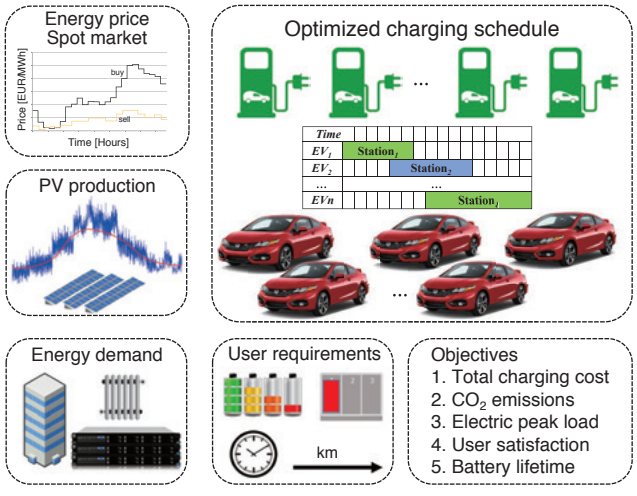


Fig. 3 Schematic overview of the components of an electromobility service

approached this problem with the quantum approximate optimization algorithm (QAOA), which is one of the standard hybrid quantum-classical algorithms for NISQ devices. One main benefit of the QAOA is the capability to find multiple optimal solutions of each problem instance in one optimization run. This was made possible since the final optimized quantum state, which encodes the solutions to the original problem, was found to be in a quantum superpositions of all the optimal solutions of the problem for many instances. Fig. 4(b) shows a summary of the statistics of the number of found optimal solutions averaged over many runs for various small instances of the problem with up to N=8 EVs. The fraction of instances, where up to 100% of all possible optimal solutions are found is rather high. Whether or not this property can be robustly found for other more realistic problems (e.g., larger N) is still open and will be investigated further.

4.2. High-dimensional qudit systems

Another research topic at HRI is the exploration of an alternative computational paradigm for quantum computing. Currently, the predominant quantum computing hardware and algorithms are based on qubits. However, a less common approach utilizes multi-level quantum systems with more than two states[30]. These are called qu*d*its and are quantum mechanical d states systems. Their multi-level nature provides a larger state space to store and process information and it is expected that this should provide some benefits for quantum computing implementations in hardware.

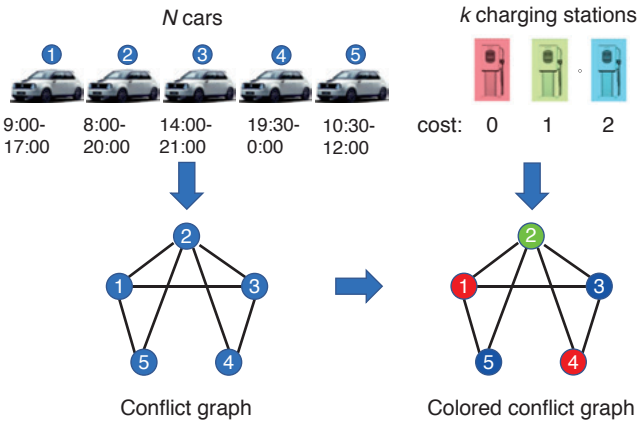
Additionally, many of the building blocks of current qubit devices, such as superconducting transmon qubits or trapped ions have more than two levels of which currently only the two lowest ones are used for actual computing. Therefore, it seems natural to extend these systems to use more than two levels and realize quantum computing hardware with multi-level qudits.

Furthermore, it is expected that qudit-based systems will be advantageous for realistic applications. Many combinatorial optimization problems require the representation of integer values, which will be much easier to achieve using qudits. For example, for the EV scheduling the assignment of an EV to one out of several charging stations can be encoded in an integer variable, whose value specifies the ID of the charging station to which the EV is assigned.

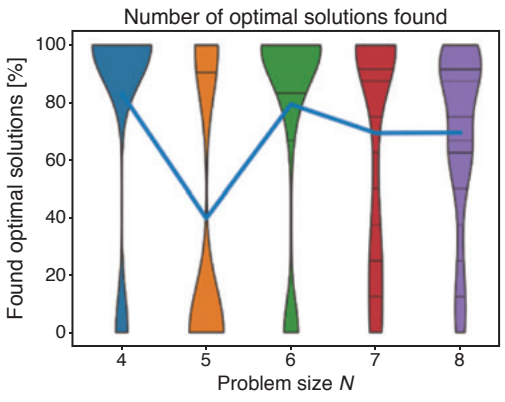
HRI is a member of the large European research project “Next level quantum information processing for science and technology” (NeQST)[31], which is funded by Horizon Europe the EU’s key programme for research and innovation. The target of the project is to advance qudit technology in the full value chain of quantum information processing. These include the advancement of qudit hardware systems realized with trapped ion quantum computers and the concurrent development of characterization and automatized design tools. Also, the end-user friendly high-level control and simulation software, which shall enable non-specialists to utilize the qudit hardware is researched. Efficient simulation of physical models such as gauge theories and practical optimization problems are major application domains for NeQST. The focus of HRI within the NeQST project is on developing and showcasing qudit algorithms for electromobility applications.

4.3. Quantum machine learning

HRI also evaluates the possible advantages of quantum machine learning approaches. As a first step, we approached classification and regression problems with variational hybrid quantum circuits using qudits[32]. A single qudit with d quantum states (levels) naturally lends itself to encoding the outcome of a multi-class classification task by associating each qudit state with one class label. With such a setup we could show that a parameterized quantum circuit



(a) Schematic problem representation



(b) Number of optimal solutions found in one run

Fig. 4 (a) Representation of the EV charging problem as a max-k-graph coloring problem
(b) Number of optimal solutions found in one quantum optimization for problems with sizes from N=4 to N=8 EVs

is able to not only learn linear but also non-linear decision boundaries in multi-class classification problems as depicted in Fig. 5. In Fig. 5(a) the left panel shows the alignment of quantum states with the class labels, while the two middle panels show the ground truth and learned classification boundaries. The achievable accuracies are shown in the right panel as function of the depth of the quantum circuit (layers). Fig. 5(b) shows the learned decision boundaries of a quantum classification circuit on the reduced MNIST dataset (left and middle panels), as well as the accuracies as function of the depth (right panel) of the quantum circuit for various numbers of classes (digits).

4.4. Quantum hardware devices for quantum sensing

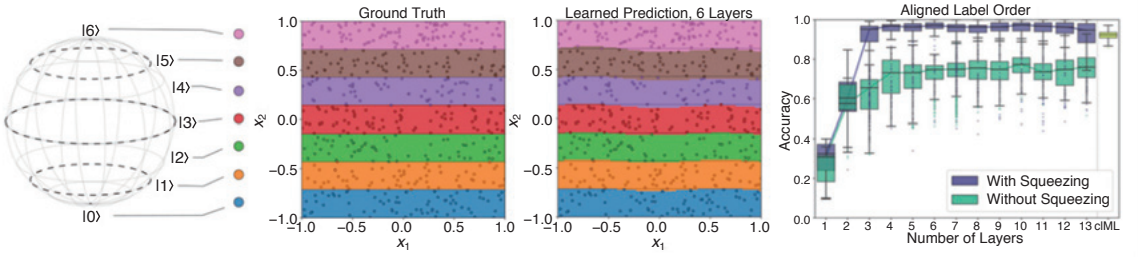
HRI has evaluated many application scenarios and has selected several specific showcases to be explored in more detail. Specifically, we are researching novel platforms for quantum magnetometers which will be useful for different applications, see Section 3.2. Each of these application fields has some requirements on the sensitivity, device dimensions, weight and power consumption. It is our strategy to first develop one common quantum platform based on solid state systems (color centers in diamond). This quantum system has been shown to enable high quality sensors of electromagnetic fields[33].

Quantum sensors in diamond, specifically, nitrogen-vacancy (NV) devices, have several potential advantages for real-world use cases. They are sensitive to very low magnetic field strengths (below 10^{-9} Tesla) and offer high orientational and spatial resolution. Also, they can be operated at ambient room temperature and have the unique property to combine optical and microwave (MW) measurements, both of which constitute an operational advantage.

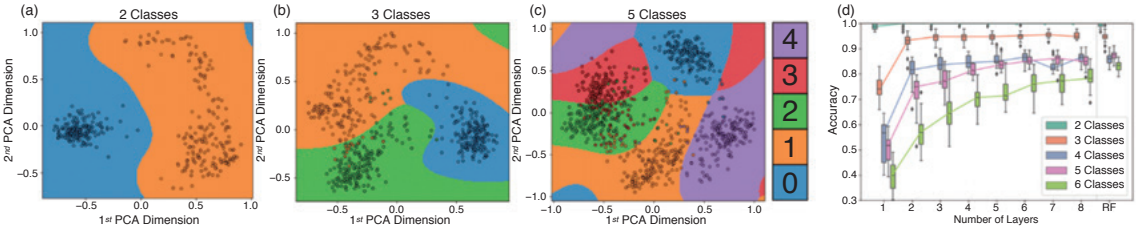
However, NV centers in diamond still encounter serious challenges. One intrinsic problem is the optical readout via excitation and fluorescence detection which destroys the information stored by the NV center. Moreover, spin fluorescence contrast is rather low which reduces the quantum information that can be read out. To overcome this problem HRI will exploit a cavity-enhanced microwave (MW) readout mechanism. This technique operates by measuring changes in an applied MW field following cavity enhanced interactions with a spin ensemble[34].

When the MW frequency is tuned to near-resonance with the NV center's resonance frequency, both absorptive and dispersive interactions occur. These interactions encode the spin resonance in the amplitude and phase of the transmitted or reflected MWs. These effects are enhanced more than ten thousand-fold by placing the ensemble in a high-quality-factor cavity resonant with the applied MWs. Dispersion and absorption by the spin ensemble then modify the resonance frequency and linewidth of the composite cavity-spin system, respectively. Consequently, detection of the transmission through or reflection from the composite cavity provides readout of the spin resonance with very high accuracy (Fig. 6).

We will employ the distributed sensing approach i.e., a collective measurement taken by N independent sensors, which can enhance the sensitivity by a factor $1/N^{1/2}$ as described earlier. Additional enhancement of the sensitivity can then potentially be realized with distributed quantum sensing with entangled sensors.



(a) Results for a stripe dataset classification task



(b) Results for reduced MNIST classification tasks

Fig. 5 (a) Results of a d=7 multi-class classification problem with data re-uploading quantum classifier circuit (b) Results of a quantum classification circuit on the reduced MNIST dataset for various numbers of classes (digits)

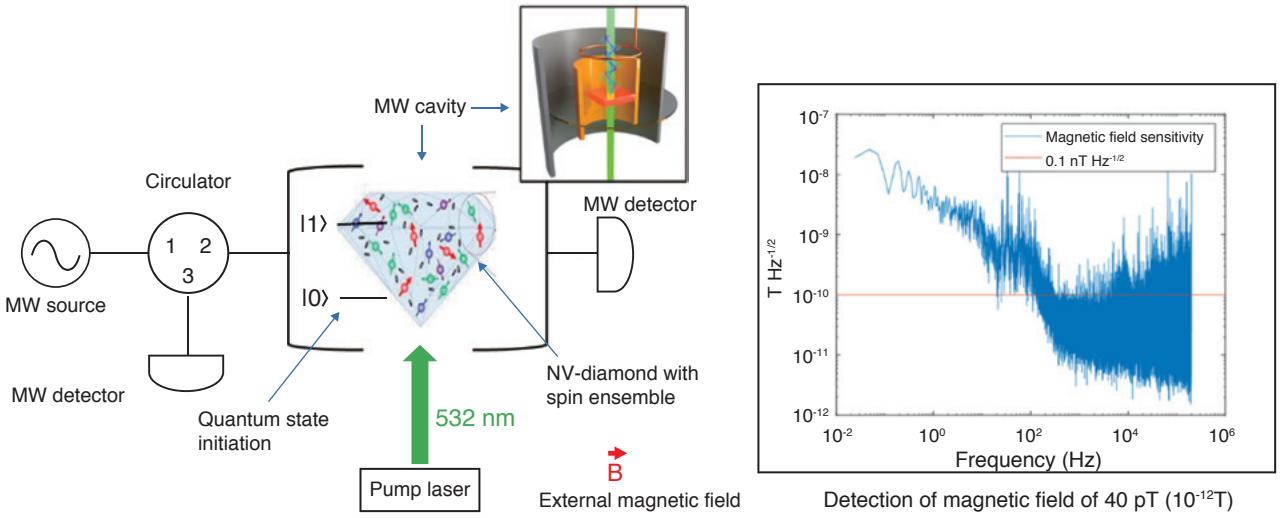
4.5. Quantum hardware devices for quantum communication

Quantum communication exploits the photon as an information carrier and the entanglement property of spatially separated photons to secure communication channels, see Section 2.5. A very important prerequisite for a successful application of photons in quantum communication is to have a high fidelity and on-demand single photon emitter (SPE) source. The requirement is that the SPE is emitting exactly one photon at a time into a given spatiotemporal mode, and all the photons are pure and coherent to ensure interference and entanglement capability of two single photons.

Current SPE technologies rely mostly on attenuated pulsed lasers, which is far from ideal as the photons then have low SPE purity. Alternatives are solid-state SPEs based on color centers in solids (e.g., nitrogen vacancy (NV) centers in diamond), quantum dots (QDs), and atomically thin two-dimensional (2D) materials[35]. The biggest advantage of solid-state SPEs is that the single photons are on demand and the purity can be extremely high (potentially >99%). 2D materials are very promising due to their high photon extraction efficiency, and because they can be readily integrated into photonic systems due to their flexibility and flat surface structure. Recently, single photon emission has been discovered in many different systems[36]. However, challenges remain like the low photon extraction efficiency, spectral inhomogeneity, and difficulty in integrating with available photonic technologies[37].

The research of HRI on quantum communication related topics is driven by the strong expertise in growing single atomic layers of 2D materials based on transitional metal dichalcogenides (TMDs)[38]. Specifically, nanoribbons of TMDs with about 10 nm width provide beneficial freedom for adjusting their electronic structure and thereby enabling single photon emission. The possibility of controlling the properties of nanoribbon-based SPE enables the engineering of several favorable properties such as increasing quantum yields, deterministic spatial positioning, or great versatility for integration with waveguides, electronic circuits, or photonic cavities for integrated quantum photonic technologies.

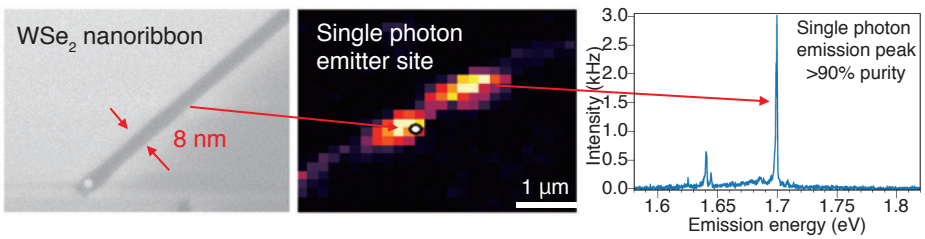
The initial results on quantum emissions obtained in the laboratory from synthesized WSe_2 nanoribbons under cryogenic temperatures as depicted in Fig. 7. Panel (a) shows a microscopic image of the nanoribbon, and panel



(a) Schematic representation of the readout mechanism

(b) Example of a detection signal

Fig. 6 Schematic representation of the cavity-enhanced microwave readout mechanism and example for a detection signal of an external magnetic field down to very small fields ($40 \cdot 10^{-12}$ T/Hz$^{-1/2}$)



(a) Microscopic image

(b) Photon emission image

(c) Photon emission spectrum

Fig. 7 Single photon emission from WSe_2 based nanoribbon as a single photon source for quantum communication

(b) shows the photo-emission optical image across the nanoribbon. Panel (c) shows the spectral resolution and intensity of the single-photon of the emitter source with higher than 90% single photon purity. These results show great potential to develop a new type of single photon emitter as light sources for quantum communications as well as other quantum applications.

5. Conclusion

Quantum information technologies have undergone rapid development in recent years. Many foundational breakthroughs have been realized and the public interest that has been generated is immense. As a result, overly enthusiastic and sometimes questionable predictions have been made. Nevertheless, there is a well-founded need for industry to increase awareness and expertise in this potentially disruptive field of research with its many observations and effects that are counterintuitive to our experience in the macroscopic world. Quantum information technologies encompass a variety of directions (computing, sensing, communication, simulation) and all of them have different states of readiness and different domains of applications. It is safe to say that all fields still face serious technological challenges while it is equally safe to say that all have realistic application scenarios in the short to midterm future. These application scenarios, some of which we have researched at the Honda Research Institutes and described above, are unlikely to demonstrate the full disruptive potential of quantum information technology. It also seems more beneficial, realistic, and impactful to demonstrate some solid and reproducible limited advantage of the first generation of quantum information technology than to expect the disruptive potential to be suddenly unleashed. Nevertheless, the potential for disruption in the long-term should also not be underestimated and nobody can say to date whether long-term will be 10 or 30 years. In a nutshell, we would summarize the current state of quantum information technology in the following statement: *the risk of not doing it simply outweighs the risk of doing it.*

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