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Research Article

Quantum Sensing in the Perspectives of Real-Life Applications

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Abstract – Amazing developing of different fundamental and applied areas of quantum science created an 'explosion' of alternative paradigms, theoretical methods, experimental approaches and numerical tools. For any particular area, for instance, quantum sensing, a researcher or an engineer who want to get a basic knowledge on the subject can feel lost facing the exponentially extending number of publications in the given field.

From one hand, now there is no need to explain the importance of the new generation of quantum devices: the accuracy and fidelity of quantum sensors to compare with their classical physics-based competitors is totally out of discussion. From another hand, observing so many different types of quantum sensors, and so many protocols of sensing, ones can ask themselves: which type of sensor or of protocol should I chose for my practical purpose? The researchers may ask themselves: which types of quantum devices have the best perspective in particular real-life applications, and which of them have rather an academic interest?

Here we develop an objective approach to evaluate quantum sensor perspectives in different real-life applications and to provide a guiding thread via the Minotaur labyrinth of different quantum approaches to the most appropriate ones.

First, we give a brief review of the most prominent quantum sensor prototypes that we have now in the market. Then, we discuss pros and cons of them in the perspective of real-life application. As a matter of our particular research interest, we also observe some control methods to improve the quantum sensing implementation for different sensor types.

Keywords – Quantum Sensors, Sensing Implementation, Fidelity, Quantum Control, Nitrogen-Vacancy-Cavity Sensors, Superconducting Qubits.

I. INTRODUCTION: DIFFERENT TYPES OF QUANTUM SENSORS

Amazing developing of different fundamental and applied areas of quantum science created an 'explosion' of alternative paradigms, theoretical methods, experimental approaches and numerical tools. For any particular area, for instance, quantum sensing, a researcher or an engineer who want to get a basic knowledge on the subject can feel lost facing the exponentially extending number of publications in the given field.

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There is a famous saying attributed to Richard Feynman: “Nature is quantum, goddamn it!!! So if we want to simulate it, we need a quantum computer” [1]. We would reformulate this sentence: Nature is quantum! So if we want to measure it, we need a quantum sensor.

Quantum sensor is a sensing engineering device that uses some quantum principles for its functioning. In other words, the working principles of any quantum sensor cannot be explained in the terms of classical paradigm and are based on principles of quantum science.

Among the basic types of quantum sensors one can mention the following [2,3]:

- Mechanical quantum sensors.
- Optical sensors.
- Atomic interferometers, including sensors with thermal atoms, cold atoms, ultracold atoms. The atoms for the sensing process are manipulated with laser field.
- Vapour cells, including nuclear magnetic resonance in vapour cells, Rydberg atoms in vapour cells, and others.
- Spin sensors, solid-state spin defects, and others.
- Superconducting sensors.

This is not a full list, and we will mention some important particular cases later.

Here we develop an objective approach to evaluate quantum sensor perspectives in different real-life applications and to provide a guiding thread via the Minotaur labyrinth of different quantum approaches to the most appropriate ones.

First, we give a brief review of the most prominent quantum sensor prototypes that we have now in the market. Then, we discuss pros and cons of them in the perspective of real-life application. As a matter of our particular research interest, we also observe some control methods to improve the quantum sensing implementation for different sensor types.

II. REAL-LIFE APPLICATIONS OF QUANTUM SENSORS

A. *Main Applications of Quantum Sensors*

The applications of quantum sensing form a very wide range covering:

- Spatial sensing: position sensing, navigation, accelerometers, and others.
- Gyroscopes, as one of the most important field of quantum sensing application.
- Timing, including clock standards.
- Gravimeters, which used not only for the fundamental science, but also for drainage, detecting underground leakage, mineshafts, underground mapping.
- Electrometers.
- Magnetometers.

Apart from that, there are some very rapidly developing fields [4]:

- Sensing for quantum computing.
- Different kinds of medical sensing and biomagnetic imaging.
- Autonomous vehicles.
- Consumer electronics.

It is obvious that the upcoming progress in consumer quantum devices (we can expect it about the years 2030s-2040s) will make the development of portable and easily operated quantum sensors absolutely necessary.

Based on [5-8], we unified the basic quantum sensing applications vs. the sensor types in the following table:

Table 1. The most efficient applications of different types of quantum sensors

	Types of quantum sensors					
Quantum sensing applications	Mechanical sensors	Optical sensors	Atomic interferometers	Vapour cells	Spin sensors	Superconducting sensors
Spatial sensing	+		+		+	+
Gyroscopes	+		+	+		
Timing		+	+			
Gravimeters			+			
Electrometers				+	+	
Magnetometers	+			+	+	+
Thermometers					+	
Barometers	+					

As one can see from Table 1, the atomic interferometers and the spin sensors have the widest areas of applications.

B. *Basic Demands for the Real-Life Applications*

Among the main criteria for the real-life application requirements one can highlight [4,6,9]:

- Price and sensing procedure cost.
- Easiness of engineering realization.
- Portability and compactness.
- High accuracy, high fidelity and the noise limitation.

Quantum fidelity quantifies how closely the results of measurements during the procedure of sensing states align with the real system states [10].

Because the commercial applications of quantum sensing virtually is just started, and the majority of devices are represented with the laboratory prototypes, we do not focus here on the prices and particular engineering realizations.

From the point of compactness, one should mention that ultracold atoms and optical sensors are champions in this item.

Regarded another important criteria, high accuracy and fidelity, there is an amazing example of the hybrid nitrogen-vacancy-cavity quantum sensor based on nitrogen-vacancy ensemble of N centers in the doped diamond coupled to a high-quality factor dielectric resonator [11]. The interesting property of such device is its ability to perform sensing with high fidelity virtually up to room temperatures [12].

III. CONTROL APPROACHES TO IMPROVE THE SENSING IMPLEMENTATION

To improve the sensor implementation one can apply control algorithms to manipulate efficiently with the sensing parameters. Often the variable to be controlled is the quantum analog of classical Fisher information [13], which is strongly related to the Cramér-Rao lower bound and defines a lower bound of the uncertainty of the value measured in the sensing process. Alternative control goals could be:

- density matrix elements for Bose-Einstein condensate (BEC),
- dephasing factor for transmon superconducting qubits,
- response for the environmental change for nitrogen-vacancy-cavity system.

The control applied to quantum systems can be classified as open-loop, where the shape of the control signal is programmed in advance, and closed-loop, where it depends on the system states and is corrected together with the dynamics of the sensing system. Among the variety of feedback methods we in our studies focused on gradient methods in the form of gradient descent algorithm or speed gradient [14,15] and, alternatively, on target attractor ('synergetic') algorithm [16].

In Table 2 we made a summary of our studies based on [17-22]. We marked the most efficient control algorithms for different types of quantum sensors.

Table 2. The most efficient control algorithms for different types of quantum sensors

Type of quantum sensor	**Open-loop (feedforward) control**	**Closed-loop (feedback) control**	
		Gradient methods	**Target attractor**
Spin-based	+		
BEC trapped in the external potential			+
Superconducting qubits	+	+	
Nitrogen-vacancy-cavity	+	+	+

According to our studies, the nitrogen-vacancy-cavity is the most flexible from the point of application of different types of control algorithms.

IV. IMPORTANT REMARKS: NUMBER OF PATENTS PER COUNTRIES, QUANTUM SENSING FOR SMART ENVIRONMENT

As a remark we mention here also the contribution of different countries to the development of quantum sensing engineering. Let's check, for example, what is the situation with the given patents.

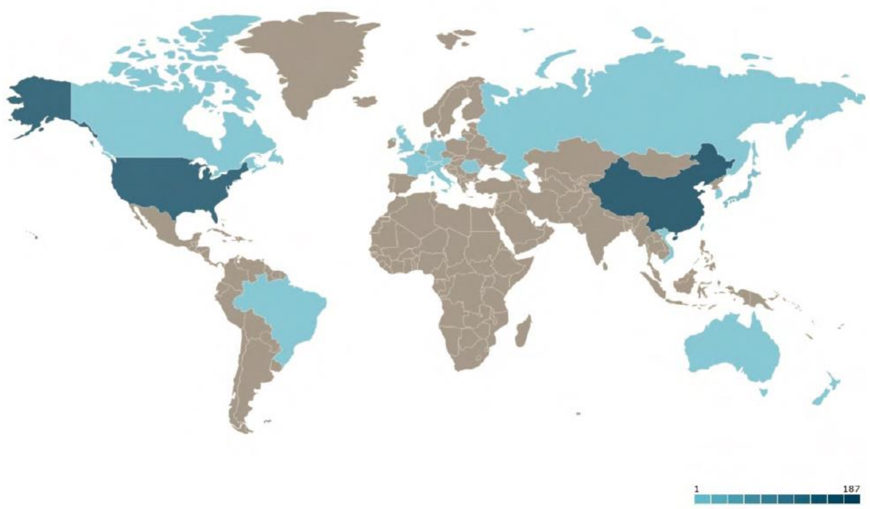

Fig. 1 Number of patents on quantum sensing cumulative to 2017 [23].

In Fig.1 one can easily see two world leaders on the quantum sensing patens applications: U.S. and China, and this tendency is preserved at least for the last 5 years [23].

Last years one can observe a complex-task demand for the real-life quantum sensing application: designing a smart environment, for example, a smart city [24-25].

V. RESULTS AND DISCUSSION

Development of quantum technologies and protocols has come close to practical and even commercial implementation of quantum sensing devices.

The efficiency of the particular type of quantum sensor for the real-life applications strongly depends on the basic parameters of quantum system: its fidelity, Fisher information and some others.

The application of feedback algorithms can drastically improve the sensing implementation, the choice of particular control algorithm can be done based on the specific type of quantum sensors.

VI. CONCLUSION

We strongly believe that nitrogen-vacancy-cavity sensors are one of the best options for the real-life applications due to their highest fidelity, accuracy and very flexible controllability properties. Superconducting qubits could be another prominent candidate.

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