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RESEARCH ARTICLE

Exploring Quantum Sensing Potential for Systems Applications

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ABSTRACT The current rise of quantum technology is compelled by quantum sensing research. Thousands of research labs are developing and testing a broad range of sensor prototypes. However, there is a lack of knowledge about specific applications and real-world use cases where the benefits of these sensors will be most pronounced. This study presents a comprehensive review of quantum sensing state-of-practice. It also provides a detailed analysis of how quantum sensing overcomes the existing limitations of sensor-driven systems' precision and performance. Based on the review of over 500 quantum sensor prototype reports, we determined four groups of quantum sensors and discussed their readiness for commercial usage. We concluded that quantum magnetometry and quantum optics are the most advanced sensing technologies with empirically proven results. In turn, quantum timing and kinetics are still in the early stages of practical validation. In addition, we defined four systems domains in which quantum sensors offer a solution for existing limitations of conventional sensing technologies. These domains are 1) GPS-free positioning and navigating services, 2) time-based operations, 3) topological visibility, and 4) environment detection, prediction, and modeling. Finally, we discussed the current constraints of quantum sensing technologies and offered directions for future research.

INDEX TERMS Quantum sensing technology, quantum sensors, quantum systems, quantum information science, quantum computing.

I. INTRODUCTION

Quantum sensing technologies (QST) utilize quantum effects to accomplish something that a conventional sensor cannot [1], [2], [3], [4], [5]. Due to quantum systems' extraordinary sensitivity to external perturbations, quantum sensors precisely monitor various physical characteristics, including temperature, pressure, frequency, acceleration, rotation, magnetic and electric fields, and more [2]. This new generation of sensors provides unprecedented sensitivity and spatial resolution performance, presenting numerous opportunities for system science and application development. Although QST is still developing, it has already attracted a great deal of interest from the community, domain experts, and researchers in numerous fields. Despite the high expectations, there is currently a lack of information regarding where and how QST can be effectively deployed and how it may affect the systems research domain [3]. Furthermore, application-oriented contributions to QST research tend to be scarce, fragmented, and narrowly focused [4].

Several quantum technologies, including atomic vapors, trapped ions, photonic qubits, superconducting circuits, and artificial atoms in wide-bandgap materials, have been used for sensing purposes in the past decade [1], [2]. Governments and businesses have recognized the need to prepare for a quantum future even though quantum computing is likely years away [3], [4]. While QST may substantially impact many aspects of humanity in the near future, QST applications area research is still in its infancy [3], [4].

To address the gap in the literature and unleash the potential of quantum sensing in systems research, we employ a systematic literature review approach that has previously led to

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the establishment of relevant results in the systems research field [5]. In addition, we intend to present a systemic perspective on the application domains that rely on the unique qualities of QSTs, as well as research concepts that are not currently being investigated. To accomplish these objectives, we designed the following study questions.

RQ1: What is the present state of QST knowledge practice?

RQ2: How useful are quantum sensors for system applications?

To answer the research questions, we methodically obtained and assessed scholarly, peer-reviewed QST publications. Then, based on the existing state of practice of QST knowledge, we emphasized connections with other disciplines and provided directions for empirical investigation. Since our objective is to establish a bridge between the QST and systems research domains, we exclude a detailed discussion about QST physics.

This study provides a comprehensive review that identifies, categorizes, and analyzes quantum sensing technology (QST) and its system domain applications. Quantum Magnetometry and Magnetoelectricity, Quantum Imaging and Optics, Quantum Kinematics, and Quantum Timing were identified as the four fundamental sensing categories. Each of these categories has the potential to produce entirely new sensing capabilities for a wide range of existing and novel implementations in system research. We discussed the challenges and provided an integrated perspective on the readiness of QST for implementing real-world applications and use cases defining four systems domains that could benefit directly from QST: 1)GPS-Free Positioning and Navigating Services, 2)Time-based Operation, 3)Topological Visibility, 4)Environment Detection, Prediction and Modelling. According to our analysis, we identified and discussed two substantial challenges. The first is the requirement for QST to address increasingly complex real-world problems, and the second is a thorough comprehension of QST's technical limitations. We anticipate that these challenges will stimulate research in the years to come.

The remainder of the paper is structured as follows. We begin with a conceptual overview of the fundamental requirements of modern science for measurements, sensors as primary measuring tools, and a comparison of conventional and quantum sensors. Next, the core technological concepts underlying QST are explained. Then, the literature review methodology and the procedures for gathering and assessing the literature are described. Finally, we discuss findings and provide examples of how QST could significantly benefit systems research.

II. CONCEPTUAL BACKGROUND

Navigation, geo-prospecting, and chemical and materials analysis are examples of applications where measurement is required. Sensors are a crucial technology that enables fundamental scientific measurements and defines the constants upon which industry and commerce depend. Quantum sensors promise to be more precise, accurate, and scalable than conventional sensors [6], [7]. This may not appear groundbreaking initially because the industry employs conventional sensors such as accelerometers, gyroscopes, and atomic clocks. However, quantum sensors have a significant impact since they outperform traditional sensing technologies by order of magnitude in three categories: drift, sensitivity, and precision.

First, conventional sensors are prone to drift, which is the accumulation of errors caused by manufacturing faults and noise [8]. For example, metal sensor components, such as springs, contract and expand in response to temperature, thus affecting measurement readings and requiring recalibration owing to drift. Quantum sensors compare relative environmental changes to absolute, immutable atomic qualities and require minimal calibration. Secondly, quantum sensors are ten times more sensitive to environmental changes due to the sensitivity of quantum states [9]. Quantum sensors can detect minute environmental changes, whereas traditional sensors cannot. Third, quantum sensors can achieve substantially higher precision [10]. Since a conventional sensor performs independent measurements, the error or noise in its data, known as the Standard Quantum Limit, is random and bounded by 1n, where n is the number of measurements. Quantum sensors utilize the quantum mechanical entanglement feature and can surpass the Standard Quantum Limit. Due to the interconnected nature of entangled particles, each environmental activity on a single particle produces comparable changes in all entangled particles. Thus, noise becomes correlated instead of random, allowing quantum sensors with entangled particles to assess environmental effects with greater precision. The measurement error for quantum sensors with all particles entangled is approximately 1/n.

Recently, a new category of applications employing quantum mechanical devices as sensors has emerged. These applications include measuring magnetic and electric fields, time and frequency, rotations, temperature, and pressure. Although quantum sensing is a relatively new research topic in quantum science and engineering, many concepts are well known in the physics community. These concepts are the outcome of decades of research in high-resolution spectroscopy, specifically in atomic physics and magnetic resonance. The atomic clock, the atomic vapor magnetometer, and the superconducting quantum interference device are three notable examples [1], [2].

Since quantum systems are often being studied at the level of a single atom, entanglement is being used as a resource for enhancing sensitivity. It is expected that quantum-enhanced sensing will considerably improve the precision with which various system parameters may be measured. Platforms for implementing new sensor protocols range from the nanoscale to the planetary scale, utilizing localized spins and photons [11]. Other platforms require the development of new science and technology. The literature reveals the scientific and technological advances necessary to meet the challenges posed by most quantum sensor platforms [12], [13].

TABLE 1. Search results.

Database	Database Selection	Search String	Abstract Review
ProQuest	847	311	48
EBSCO	315	11	4
Springer	280	105	6
IEEEXplore	121	5	2
Scopus	94	79	14
Web of Science	85	48	24
Total	**1742**	**559**	**98**

TABLE 2. QST experiment-proved fundamentals.

QST	Empirical Validation	Publications
Photonic	16	24, 40, 41, 50, 51, 52, 57, 58, 63, 64, 104, 116, 117, 120, 132, 136
Nitrogen-vacancy and Magnetic-resonance	33	25, 28, 34, 35, 36, 37, 42, 43, 53, 55, 56, 66, 67, 68, 75, 77, 79,81, 107, 108, 109, 110, 111, 114, 115, 118, 119, 122, 125, 130, 133, 134, 135
Ion-trap and Optical-lattice	6	30, 31, 106, 113, 121, 128
Superconducting and quantum dots	3	54, 105, 127
Total	**58**	

III. SYSTEMATIC LITERATURE REVIEW PROTOCOL

We adopted a systematic literature review framework for information systems research [5]. This framework was selected because it determines the literature review's methodology by integrating and incorporating the most significant elements and procedures from seminal works on literature review methodologies in software engineering [14], social sciences [15], health sciences [16], management and organization science [17], and information systems [18], [19]. The following sections summarize the key activities performed in accordance with the selected methodology.

A. PLANNING AND SEARCH STRATEGY

The primary work with databases was performed in May 2022. We began by identifying the most relevant databases. The ''quantum sensing'' search query, which was confined to scholarly peer-reviewed papers published between 2018 and 2022, lead us to focus on the following databases: ProQuest (847 publications), EBSCO (315), Springer (280), IEEEXplore (121), Scopus (94), and Web of Science (85) results accordingly. We built and tested the detailed search criteria based on the research questions until the final search query was defined. Since the focus of this review was to identify the potential for implementing quantum sensing in real-world scenarios that arise from conducting trials or demonstrations, the final search query contained ''quantum sensing'' AND sensor* AND (prototy* OR PoC OR MVP OR device*) AND (demonstrati* OR implementati* OR empiric*).

While the first two parts of the query were dedicated to eliminating purely theoretical studies, the last element aimed to identify only the articles that described implementation, testing, or demonstration of the sensors or sensor's-based applications. Table 1 summarizes the number of articles per selected database.

B. FILTERING STRATEGY

The final search query yielded 559 items, as shown in Table 1. Based on the abstract review, those results were vetted, yielding 98 publications. These 98 publications were further screened for duplicates, leaving 89 documents for an in-depth content analysis of the articles. Next, we eliminated publications dealing with simulations, supervised and machine learning, quantum physics, and QKD and review articles. The remaining 71 documents were examined according to the research questions. Since the purpose of this research is to determine the applicability of quantum sensing to system applications, articles dealing with biological or chemical applications have also been omitted. This phase of screening yielded the final 58 articles for in-depth analysis.

IV. THE PRESENT STATE OF QST

This section contains the answers to RQ1: What is the present state of QST knowledge practice?

A. QST MAIN TECHNOLOGY CATEGORIES

Based on the review results, the technologies that have matured to the point of experimentation comprise four major categories. These are: a) Photonic technologies; b) Nitrogen-Vacancy and Magnetic-Resonance technologies; c) Ion-Trap and Optical-Lattice technologies; and d) Superconducting and Quantum Dots technologies. Table 2 summarizes the results of this analysis by technology.

1) PHOTONIC QST

Photonic QST research is a very active field. It focuses on employing photons to perform quantum information communication tasks. In addition, this field examines the principles of quantum mechanics and entanglement to develop novel quantum information applications. In recent years, photonic quantum sensing has been transformed by ultrabright quantum light sources with decreased noise and entanglement and by discovering unique approaches for constructing practically relevant quantum states and measurements [21]. Multiple-photon interferometry with weak field homodyning has recently exhibited possibilities beyond the existing limit and may significantly improve phase-detection resolution [20]. For the first time, quantum microscopy with NOON states was utilized to demonstrate the possibility of capturing images utilizing fragile quantum states [21]. Quantum-correlated photon states and compressed light states can also be used for quantum-enhanced sensing [22]. Squeezed light strategies for next-generation telescopes are being developed utilizing next-generation gravitational-wave detectors [23]. Ongoing efforts in integrated quantum photonics rely on the fabrication of quantum photonic integrated circuits, which may be globally or locally integrated. However, chip-scale integration is essential for scaling up and transforming laboratory demonstrations into practical technology [20].

2) NITROGEN-VACANCY AND MAGNETIC-RESONANCE QST

These technologies utilize the electron and nuclear spin degrees of atoms and molecules' freedom in solids, such as nitrogen-vacancy centers, thus promising a long coherence due to their effective environmental shielding [24], [25]. Optical control is used for spin initialization and spin readout, whereas microwave fields are used for single-qubit gates. Multiple spins can use magnetic dipolar interactions or long-distance optical coupling to build two-qubit gates. Some preliminary studies on high sensitivity magnetic field sensors with temporal imaging and micro-PL setup with confocal scan were addressed in the review [24], [25], [26], [27], [28]. However, regardless of recent advances, nano-positioning errors continue to be a serious and pressing issue.

3) ION-TRAP AND OPTICAL-LATTICE QST

Both ion-trap and optical-lattice QST are now under investigation. These two types of QST cover a wide range of phenomena, including neutral atoms in optical lattices, singly charged ions and molecules, highly charged ions, and even nuclear transitions. Although neutral atoms have a high signal-to-noise ratio, they are generally more vulnerable to external fields and collisional shifts. As a result, the environment in which neutral atoms are maintained must be carefully managed. On the other hand, setups for analyzing a single ion can be relatively simple and require less complex technology to achieve the same degree of precision as their counterparts that study neutral atoms, but at the expense of longer averaging times. Some representative publications utilizing these technologies are works of [29], [30], and [31].

4) SUPERCONDUCTING AND QUANTUM DOTS

The development of quantum dots and superconducting technologies QST are among the most promising technologies for creating a quantum computer in the real world. Quantum dots are nanostructures comprised of semiconducting materials constructed to contain a small amount of electric charge - a few electrons. Quantum dots may be treated as adjustable artificial atoms controlled by an external gate. When contacted by conductive leads, a quantum dot can become the active component of a single-electron transistor, an extremely conductive device at very particular gate voltages.

In recent years, complicated hybrid devices, particularly superconductor-semiconductor heterostructures, have garnered considerable interest. The physics of interacting quantum dots connected to superconducting leads at absolute zero is now well known. The qubit coherence durations of superconducting qubits must be compatible with a quantum processor, often implemented by a conventional computer. Despite being lithographically scalable and compatible with the methods used to manufacture semiconductors, superconducting qubits have their distinct challenges. According to a recent study, coherence time limitations result from material loss issues at various material interfaces in superconducting junction configurations [32].

TABLE 3. QST experiment-proved prototypes.

Database	Experiment-Proved Prototypes	Publications
Quantum Magnetometry and Magnetoelectricity	30	25, 28, 31, 34, 35, 36, 37, 40, 41, 42, 43, 105, 106, 107, 109, 110, 111, 112, 114, 115, 116, 118, 119, 122, 125, 130, 133, 134, 135, 136.
Quantum Imaging and Optics	15	24, 50, 51, 52, 53, 54, 55, 56, 57, 58, 63, 104, 113, 117, 120
Quantum Kinematics	8	30, 66, 67, 68, 75, 77, 79, 81
Quantum Timing	5	29, 63, 64, 108, 132
Total	**58**	

B. QST MAIN SENSING CATEGORIES

According to the literature analysis, QST can be classified into four basic sensing categories: quantum magnetometry and magnetoelectricity, quantum imaging and optics, quantum kinematics, and quantum timing. Each of these categories has the potential to generate entirely new commercial products or industries. In the following sections, we briefly describe the categories and discuss empirical results demonstrating the advantages of QST over conventional sensors. Table 3 shows the results of the analysis according to four key sensor categories.

1) QUANTUM MAGNETOMETRY AND MAGNETOELECTRICITY EMPIRICAL RESULTS

One of quantum metrology's most essential and crucial jobs is accurately measuring a magnetic field. Over many years, quantum magnetometry was researched using a parallel method that uses entangled probe states. While the ultimate precision for quantum magnetometry with a single parameter is well recognized, the utmost accuracy can be reached with entangled probe states that use all magnetic field components. Multi-parameter quantum magnetometry can be used to calibrate the ultimate capabilities of quantum reference frame alignment, quantum gyroscopes, etc [33].

According to the review results, the major category is quantum magnetometry and magnetoelectricity, with a total of 30 publications out of 58. Most publications in this category reported on the empirical results obtained by sensor prototypes. Here are a few examples. Kim et al. [34] reported the results of quantum magnetometry and simultaneous thermometry with a sensitivity of 32.1 μT Hz$^{1/2}$. The sensor has a footprint of 200 μm × 200 μm and was built with CMOS technology. Additional example of a CMOS-NV-based prototype constructed on a similar architecture revealed the sensitivity of 245 nT/Hz$^{1/2}$ [35]. The study of potential use of magnetometers with the NV centers for biomedical applications revealed that they could detect the micromolar concentration of MNPs at distances of a few millimeters with a minimum detectable AC magnetic field of 57.6 nT at a frequency of 1.025 kHz during a one-second measuring period [36]. Additional examples of the studies in the field are a hybrid magnetometer for applications in biomagnetism and geomagnetism [37] and a portable fiber-based NV magnetometer with a sensitivity of 344 pT at Hz$^{(-1/2)}$ [28]. The latest utilizes the NV and magnetic-resonance QST and has the sensitivity potential that can be advanced to 11fT/Hz$^{1/2}$at 100 Hz.

Magnetoelectricity is most evident in antiferromagnetically ordered materials, where an electrically induced magnetization is not masked by the system's natural magnetization [38]. Quantum electric dipole liquid, analogous to quantum spin liquid in magnets, can be predicted in dipole lattices if quantum fluctuations and geometric frustrations are simultaneously fulfilled [39]. Additional research demonstrated a microwave electric field sensor with the sensitivity of 55nVcm^{-1}Hz$^{-1/2}$ using a simple setup [40]. The researchers argued that the minimum detectable field that could be achieved is 780pVcm^{-1}, which is three orders of magnitude smaller than existing atomic electrometers. According to the researchers, the applications of technology are diverse, including radio astronomy, radar technology, and metrology. In turn, the research of Jaffe et al. [25] reported experiments maintaining diamond crystal quality with the highest documented nitrogen concentration in a delta-doped layer (1.8 × 10^{20} cm^{-3}). These experiments might pave the path for highly sensitive NV-based magnetometers. Additional promising works that require attention are Lescanne et al. [41] and Maayani et al. [42]. While the first work offered a new class of low-noise nonlinear microwave detectors, the second reported on a distributed quantum sensor that was tested in a water-immersible 90-m-long cable [42]. It demonstrated a sensitivity of 63 $^{+/-5}$ nT Hz$^{(-1/2)}$ per each one of 102 detection sites. Finally, Oliver et al. [26] described the results of experiments with a strapline-based, planar, shaped microwave antenna that enables manipulation of NV spins of up to 10 MHz in an ensemble of NV centers.

2) QUANTUM MAGNETOMETRY AND MAGNETOELECTRICITY EMPIRICAL RESULTS

With 15 publications out of 58, quantum imaging and optics is the second largest category. Various techniques and protocols can be used in quantum imaging systems. For example, single photon avalanche detectorscan measure the flight time from a source to an object, allowing the distance to the object to be calculated [43]. Photon avalanche detector arrays can be used to build a 3D camera. In turn, two-photon imaging (or quantum ghost imaging) employs the quantum entanglement principle [44]. In quantum ghost imaging, entangled photon pairs are produced, one photon is sent through the object being imaged, and the other is sent to a detector. Consequently, photons that have not physically interacted with the object are utilized for ghost imaging. The detector learns about the object by measuring photons that have not passed through it, also known as a ghost image. The primary advantage of quantum imaging is that the signal to noise ratio (SNR) of a measurement can be better than with conventional light [45]. However, one limitation of ghost imaging is the inefficient imaging speed. The number of measurements required to reconstruct the image, determines imaging speeds, which scales quadratically with the required resolution [43]. It imposes a practical limit on applications that require high-resolution images. Attempts to improve and enhance image quality and resolution focused on employing a pseudo-inverse ghost imaging technique via a sparsity constraint [46], employing a Schmidt decomposition for image enhancement [47], and imaging based on Fourier spectrum acquisition [48].

Here are some representative works that contain empirical results in quantum imaging and optics. Drougakis et al. [49] demonstrated a new optical beam steering technique on optical breadboards for fiber-to-free-space-to-fiber coupling schemes with a fiber-to-fiber coupling efficiency of more than 89.8%. When compared to traditional techniques, this solution provides increased precision, accuracy, and stability of beam direction and position. According to the researchers, this technique, can be useful in quantum experiments involving space-based quantum sensing. Mousa et al. [50] conducted experiments with an integrated semiconductor photonic switch based on cesium, rubidium, or potassium atoms spectroscopy. These switches, according to the researchers, could be used in quantum sensors for near-infrared wavelengths. The results obtained with the 890-920 nm device allow operation in the wavelength ranges 750-780 nm and 745-775 nm. Similarly, additional research presented an on-chip single-photon spectrometer with more than 200 equivalent wavelength detection channels with further scalability [51].

Concerning the potential of a new generation of currently available devices and applications, Ziem et al. [52] claimed that they enhanced multiplexed MRI to improve ensemble sensitivity and field of view by demonstrating the imager's point spread function to approximately 100 nm, with further potential to achieve approximately 40 nm. Liu et a.l [53] discussed how micro-light-emitting diodes with quantum dots could be used in display technology. Scholten et al. [54] demonstrated a widefield optical microscope capable of mapping local quantities such as magnetic field, electric field, and lattice strain. Finally, Krzyzewski et al. [55] described a magnetographic proof-of-principle camera with a sensitivity of 200 feet per root Hz and a pixel size of 100 micrometers. Mateusz et al. [56] successfully implemented a time-inversion interferometer with a resolution of 15 kHz using 20 times fewer photons than a conventional method. This achievement paves the way for applications in optical communication channels or signals transduced from lower-frequency domains. In turn, Muhammad et.al. [57] described the results of using a short-wave infrared hyperspectral line camera, which increased the dynamic range of hyperspectral imaging from 43 dB to 73 dB. According to the researchers, the method enabled the accuracies of up to 98% for the food and up to 95% for the polymer waste classification.

3) QUANTUM TIMING EMPIRICAL RESULTS

According to the literature, quantum clock experiments focused on three main domains: a) clock stability, b) quantum clock synchronization, and c) interior navigation. A hybrid atomic-quantum clock is an atomic clock with laser-cooled quantum elements consisting of single ions trapped in an electromagnetic ion trap. Atomic clocks are accurate due to the immutable fundamental properties of a particular type of atom. Atomic clocks depend on laser interactions with these atoms. Because minor errors in the clock cause the laser's frequency to stray from the ideal, the frequency of a laser must be kept at a frequency determined by the atoms. An interferometer is used to monitor this deviation to adjust the clock. However, since an interferometer can accommodate only a certain number of atoms, additional atoms are necessary for more precise measurements. The difference between the sensitivity of conventional interferometers and entangled interferometers is roughly proportional to the square root of the number of atoms in the system and the number of atoms. For example, using 10,000 atoms enables 100 times more sensitivity. Currently, no operational atomic clocks rely on this principle. Recent studies demonstrate a prototype interferometer comprised of 26 ions [58], which significantly reduces interferometer noise in comparison to earlier studies that used ten ions [59] and 15 ions [60].

In addition to incorporating quantum elements into atomic clocks, recent research in the field of quantum metrology defines native quantum clocks, which measure time through measurements of quantum systems serving as clocks. Recent empirical research demonstrates that quantum clock precision has matured significantly. For example, while the laser-based atomic clock has a constant output, frequency precision of 7.8×1018 photons per second [61], the latest prototype of quantum optical lattice clocks has demonstrated a frequency precision of 2.5×1019 [62].

As high-phase coherent lasers evolve, optical atomic clocks powered by multiple atoms have reached the standard quantum limit with remarkable stability. The number of atoms that may be queried and the time that passes determine the conventional quantum limit [60]. In a recent empirical study, a field test of two-way quantum clock synchronization between two nodes 7 kilometers apart achieved significantly improved time stability of 1.9 picoseconds at 30 seconds [63]. The results of this experiment provide a solid base for achieving two-way quantum clock synchronization in real-world systems with the potential for sub-picosecond precision for advancing field applications such as network clock synchronization and quantum key distribution.

4) QUANTUM KINEMATICS EMPIRICAL RESULTS

Quantum Kinematics is associated with high-precision inertial measurement, which is vital to fundamental research and applications [64]. Monitoring minute changes in acceleration can provide information about the terrain and the surrounding environment. Recently, quantum kinematics sensors have emerged as a powerful quantum system that combines the outstanding consistency characteristics and monitoring mechanisms of atomic systems with the tiny dimensions and construction capabilities of solid-state equipment [65], [66], [67]. According to the review results, the accuracy of quantum kinematics sensing measurements of high-precision rotation and acceleration has improved significantly compared to that of classical systems. Quantum kinematics applications could mainly be found in quantum gyroscope and accelerometer fields.

Ring-laser gyroscopes and fiber-optic gyroscopes, whose concepts were developed at the beginning of 1990, have traditionally held the records for precision and bias stability among commercially available gyroscopes [68], [69], [70]. Their precision is related to the surface area of the optical light path. While significant progress has been achieved in miniaturizing this type of devices, fundamental constraints in its size and sensitivity remain difficult to overcome [71]. On the other hand, microelectromechanical system gyroscopes are widely used for mass production in consumer electronics. Although these devices' bias stability is typically insufficient for reliable long-term inertial navigation, they offer outstanding power consumption characteristics, chip-scale dimensions, and reasonable pricing [73]. Despite significant progress in improving bias stability and accuracy, there is still a substantial gap between compact and accurate devices [66].

Due to the scientific and technological importance of inertial surveying technology based on the nitrogen-vacancy (NV) centers in diamonds, the NV center is one of the most studied platforms in the rapidly emerging field of QST. NV-based gyroscopes enable the creation of devices with smaller sizes and greater precision. While existing gyroscope sensors based on fiber-optic and meter-scale ring laser achieve sensitivity to the rotation of 2.2×10^{-5} with 107 atoms, the latest research achieved 2.7×10^{-5} with 107 atoms [74]. The diamond's NV center has demonstrated exceptional properties as a solid-state spin system. It has optically observable electron spin, a long coherence time at ambient temperature, and the capacity to optically polarize the spin state, making it an ideal option for scalable, precise measurement and miniaturized quantum gyroscopes. A ring laser gyroscope with a larger size and lower sensitivity than the NV-based gyroscope has been demonstrated in several articles: 10^{-11} [70], 10^{-9} [75] and 10^{-8} [69]. The next generation of atomic spin gyroscopes have higher sensitivity and a medium size comparable to the SERF gyroscope's 10^{-8} sensitivity [71].

The significant advancement in the field of quantum accelerometers is evident. Accelerometers have been widely used as weak force probes in a variety of applications, including inertial navigation, land-based resource exploration, and seismic monitoring. There are numerous types of accelerometers, including capacitive, piezoelectric, tunnel-current, thermal, and optical [76]. These accelerometers' performance is highly dependent on the fabrication of the displacement sensors, resulting in direct technical limitations in bandwidth, quality factor, and noise [77]. Conventional mechanical accelerometers have wide bandwidths that are suitable for navigation applications, but they suffer from bias and scale factor drift over time [78]. The high sensitivity of optical accelerometers has garnered a great deal of interest among the various types of accelerometers. Nonetheless, shot noise severely limits the sensitivity of such accelerometers. The research on advancement of accelerometer is currently guided by the development of methodologies and techniques to reduce sensor noise and eliminate their limitations.

Since their initial demonstration in the early 1990s, atom-based accelerometers [78], [79] have demonstrated accuracies of up to 10 ng. Consequently, they were considered for the next generation of inertial navigation systems. However, sensors based on cold atoms typically have a narrow bandwidth, low repetition rates, and dead times during which no inertial measurements can be made. The recent research suggests an enhanced quantum accelerometer based on atom-light quantum correlation, consisting of a cold atomic ensemble, light beams, and an atomic vapor cell [76]. The findings revealed a quantifiable acceleration range of up to 23 ng and a bias stability of 1.59×10^{-5}g.

An additional direction in quantum acceleration is the development of a three-dimensional quantum accelerometer that is based on matter-wave interferometry and can measure three orthogonal accelerations, each concerning an independent inertial reference frame defined by the surface of a mirror. On each axis, the 3D quantum accelerometer utilizes correlations between atoms and a mechanical accelerometer attached to the back of each reference mirror to create a hybrid quantum/classical accelerometer. This system combines the high sensitivity and precision of atom interferometers with conventional devices' wide bandwidth and dynamic range. One can precisely track the entire acceleration vector by independently correcting each conventional accelerometer. These accelerometers have bias stability of up to 5×10^{-6} g and white noise of up to 1×10^{-5} g/$\sqrt{\text{Hz}}$ [80].

V. QST POTENTIAL USABILITY FOR SYSTEM APPLICATIONS

While the previous section was dedicated to answering RQ1 about the present state of QST knowledge, in this section, we discuss potential uses for quantum sensors that have been demonstrated empirically. Hence, by answering RQ2 about the usefulness of quantum sensors for system applications, we establish a connection between QST and their real-world applicability for addressing various challenges in diverse use cases.

A. GPS-FREE POSITIONING AND NAVIGATION SERVICES

The Global Positioning System (GPS) shows the effectiveness of precise time measurement. GPS clocks have a high precision, but they drift over time [81], and each satellite synchronizes its internal atomic clocks with a ground station twice daily. While GPS is required for most navigation systems, GPS cannot always operate with high degree of reliability because the GPS signal is either obscured, jammed, or spoofed. The unreliability or lack of service provided by GPS in urban areas, high latitudes, or the subsurface poses a significant challenge to locating and navigation applications. For example, if GPS signals are disrupted, autonomous vehicles that rely extensively on satellite navigation may have safety and operational issues [82]. While researchers and industry vendors work to develop technologies that enable continuous localization and safe control of autonomous vehicles even in the absence of a GPS signal, there is still a significant gap between existing technologies that support precise, accurate, and sustainable positioning and time [82].

GPS's vulnerability has reduced confidence in the system, forcing the creation of countermeasures. At the same time, there is a growing demand for high-precision navigation solutions that work independently of GPS [81], [83]. These solutions should be capable of starting in a GPS-free area and operating under challenging conditions. Among the proposed solutions enabling GPS-free positioning to overcome navigational issues are inertial navigation [84], reference-aided navigation [85], and radio frequency signals-based navigation [86]. Nevertheless, none of these solutions are ubiquitous, and they all have constraints that prevent their general adoption. For example, insufficient light, dispersion, and refraction restrict the use of optical navigation systems. In addition, traditional inertial navigation loses precision over time due to the drifting issue.

The literature review results indicate that quantum sensors can provide GPS-independent, precise, and reliable inertial navigation. Quantum inertial sensing uses quantum gyroscopes and accelerometers to sense angular and linear velocity changes. Hence, the quantum inertial navigation system might be composed of a quantum gyroscope, a quantum accelerometer, and quantum clocks.

Undersea navigation, which presents major obstacles due to the rapid attenuation of electromagnetic waves, is an additional and specific case of navigational challenges [87]. The magnetic anomaly-based mapping procedure is complex and time-consuming [88]. Acoustic technology, including ultra-short baseline localization devices, is used in conventional underwater navigation operations. Nevertheless, they are plagued by a poor rate of recency, limited bandwidth, environmental problems, and costly pricing. Quantum inertial navigation can also be performed by combining sensitive quantum magnetometers with a map of the Earth's magnetic anomalies. Hence, for example, quantum gravimeters and magnetometers have the potential to serve as the basis for a quantum navigation system for submarines. This strategy would be particularly useful in submarine gorges, wavy seafloors, and littoral zones.

Even though the individual sensors required for quantum inertial navigation have been demonstrated in the lab, it is still challenging to construct a quantum inertial measurement unit. As the quantum inertial navigation device decreases in size, its deployment is expected to increase. However, the extent to which one can miniaturize remains uncertain. In addition, various questions exist about the implementation of quantum inertial navigation on a chip. It is undoubtedly a cutting-edge, albeit formidable, technology. Consequently, we believe that a hybrid system that combines the outputs of conventional and quantum accelerometers can serve as a bridge between traditional and quantum inertial navigation.

B. TIME-BASED OPERATION

Time synchronization is essential for ensuring the reliability and security of a network. Typically, each network node has its own oscillator-driven clock. In a networked system, where different nodes may possess different types of clocks, the clocks are powered by oscillators that are not identical. Time synchronization in networks is typically performed in two primary ways. Installing independently synchronized clocks at each network node or utilizing packets to synchronize widely dispersed clocks is the first option. The IEEE 1588 standard mandates that timing messages be transmitted from a master reference clock to slave clocks via a communication network. However, oscillator-driven clocks' limitations lead to timing errors. In addition, if the independently synchronized clocks rely on GPS timing, the GPS technology's limitations make them vulnerable to cyberattacks. When synchronizing virtual environments on software-defined networks, additional synchronization errors may occur [89]. The second option for time synchronization is to deploy an atomic clock for each network device [90]. However, the second method is not applicable in most cases due to its high cost. Because of these factors, datagram-based approaches cannot meet the increased precision and security needs of mission-critical services in future communication networks.

Quantum clock synchronization is more precise than GPS because it employs the femtosecond correlation between entangled photons [4], [91]. The quantum clock synchronization protocol defines communication between two nodes separated by an unknown distance in time and space [4]. A master quantum clock could be installed in a local network of directly connected slave quantum clocks. Then, a free-space or fiber-optic link can be created between every source and receiver of entangled photons. This connection will enable the master clock to transmit ultraprecise timing data to its quantum slave clocks on the order of picoseconds or less. Their arrival time is recorded upon the arrival of photons [91]. Regardless of node distance, the time difference between clocks is derived from data cross-correlation. We believe that employing quantum clock synchronization paves the way for future communication networks to meet the need for increased precision and security.

C. TOPOLOGICAL VISIBILITY

Knowledge of underground gravel and earth conditions is essential for various applications, including oil and gas exploration, mining, construction, and landfill management. Traditional surveying methods have difficulty advancing in these areas, but QST promises to make substantial progress in this area of research. The high sensitivity of quantum gravimeters enables them to detect significantly smaller objects at greater depths than conventional gravimeters. Thus, the first practical applications of quantum magnetometry and quantum gravimetry help to investigate continents and sea surfaces, as well as natural underground changes.

Quantum gravimeters offer high precision, which can enhance or introduce new applications, including geophysics research, seismology, archaeology, mineral and oil detection, underground scanning, precise georeferencing, and topographic mappings. Numerous papers consider high-resolution quantum magnetic sensors and quantum gravimeters. Detection, discovery, and localization of underground structures such as caves, tunnels, and bunkers are among the possible applications of these sensors cited in the literature [92]. Even though the sensor must be relatively close to the ground to achieve good resolution, its sensitivity may enable new applications, such as rapidly clearing brownfield sites or searching for minerals. While the sensor head is remarkably sturdy compared to other devices, the necessary auxiliary hardware is still relatively large and complex [93]. As a result, we anticipate an increase in the number of applications for underground visibility that drives technological advancement, resulting in cost and size reductions.

Prediction, detection, and mapping of topological environments with an emphasis on subterranean and subaquatic visibility pose significant difficulties [40]. To address these obstacles, multiple sensing technologies are required. GPS technology is ineffective in underground conditions, and inertial navigation is one possible solution. Quantum inertial navigation has the potential, as discussed, to circumvent certain limitations in the field. We argue that quantum gravimeters and magnetometers could potentially serve as the basis for quantum-enhanced submarine navigation, especially in deep-sea canyons, wavy seabeds, and coastal environments.

D. ENVIRONMENT DETECTION, PREDICTION AND MODELLING

Quantum imaging has numerous applications and can overcome the limitations of today's conventional imaging systems in terms of resolution, SNR, contrast, and spectral range. Examples of quantum imaging devices are 3D quantum cameras, behind-the-corner cameras, low-brightness imaging, and quantum laser imaging, Detection, and Ranging (LIDAR) devices. Quantum imaging encompasses two primary research subfields: single-photon and two-photon imaging [20]. Due to recent advances in quantum technology, single-photon imaging could enhance the capabilities of 3D LiDAR [94]. Short-pulse lasers and a Single-Photon Avalanche Diode (SPAD) can be used for non-line-of-sight imaging, also known in the literature as seeing around corners or behind walls.

SPAD uses optical and near-infrared spectral regions and is sensitive enough to detect a triple-scattered signal. The SPAD array is a highly sensitive single-photon detector coupled to a pulsed illumination source that measures the time of flight between the source and an object and, thus, the distance. When placed in a matrix, SPAD can function as a 3D camera. Using a SPAD array permits the detection of objects beyond the line of sight, such as those concealed behind the corner of a wall. The concept's viability depends on the cooperation of a camera and a laser. The laser will transmit a pulse in front of the SPAD camera. The laser pulse scatters in all directions from the spot, including behind the corner, where photons can be reflected from the spot before the SPAD camera and then to the camera itself. One application of non-line-of-sight imaging is the prevention of vehicular and pedestrian collisions. This capability is essential for autonomous vehicles and has driven advancements in non-line-of-sight imaging. The first solutions in the field were developed by combining a femtosecond laser with a fast imager [95] or a streak camera [96].

Two-photon or Quantum Ghost Imaging (QGI) involves using distinct yet spatially correlated groups of photons to reconstruct an image from a series of measurements of a single pixel. The primary objective of the QGI approach is to reconstruct images with the highest resolution and quickest acquisition times. The QGI could be helpful in harsh environments or inaccessible areas where a standard surveillance camera would be ineffective. The practical benefits of QGI derive from the fact that two photons can be employed for independent measurements, even though only one interacts with the sample. It means that two distinct types of information can be obtained simultaneously, maximizing the amount of information extracted from the available photons. For example, the bucket detector could be replaced with a spectrally resolving detector array, enabling the acquisition of multispectral ghost images and, consequently, the acquisition and modeling of the 3D geometry of an object [97].

Although the discussed methods have fundamental advantages over traditional measurements, it is necessary to address several technological obstacles related to realizing improved SNR in a manner that applies to applications. In addition, image acquisition measurement times should be reduced from minutes or even hours to the range of seconds, and more photon pairs should be generated [98]. To summarize, quantum imaging has significant and revolutionary application potential. Despite technological progress and demonstrated prototypes, the field of environment detection, prediction, and modeling will take some time to produce commercial products.

VI. CHALLENGES AND FUTURE DIRECTIONS

Based on the identified current state of practice derived from the answers on RQ1, in this chapter, we discuss the challenges of QST's adoption and offer some directions for future research. In particular, we examine the technological and business obstacles to incorporating QST into practical applications. Among the technological obstacles, we discuss implementation issues such as temperature regimes and field-ready device dimensions. From a business standpoint, we discuss the price of technology as one of the barriers to the widespread commercialization of QST. In addition, considering the answers on RQ2, we discuss future directions for the usability of quantum sensors for system applications and various use-cases.

A. CHALLENGES

The QST has higher sensitivity and a faster response time than traditional sensors. However, they require an effective cooling system. For instance, small Stirling-type coolers in cameras can cost around $70,000. An additional example is a 369GaN project, developed in 2022 by the UK National Quantum Technologies Program, which requires a laser that operates at a wavelength of 369nm. It can only be accomplished by a large, complex, and highly pricey laser, which confines the technology to the laboratory setting. It is anticipated that the technological progress with cooling equipment will reduce the dependence on energy-intensive computing resources.

In the near future, QST research is anticipated to produce a highly efficient and deterministic single-photon source. In the meantime, photon-based QST is still immature, expensive, and necessitates cryogenic cooling. Although significant progress has been made in developing semiconductor laser platforms, it is unlikely that some of the more complex functional requirements will be satisfied using this method. The lack of reliable narrow linewidth lasers with reduced size, weight, power, and cost hinders the commercialization of ion-trap and optical-lattice QST and specific cold-atom-based quantum instruments.

Temperature problems also constitute challenges for the NVC-based QST. Research is ongoing on reducing the probe's temperature by enhancing its thermalization, making microwave delivery more efficient by using less power, and creating a resonant optical readout. Shortly, it may be possible to realize NVC-based QST and improve its performance, particularly in terms of cooling and precision. Further research is also required to achieve precise position detection of the nanodiamond. One of the promising research directions for improving the detection sensitivity is enhanced fluorescence detection methods [72].

In the field of optical clocks, empirical results revealed the efforts in creating an optical lattice with high power and narrow linewidth. A laser with tuning capabilities is used to perform this function in most instances. These lasers are typically large and delicate equipment costing approximately $100,000. This technological complexity and cost pose a substantial barrier to commercializing instruments based on interferometers that can be used outside a laboratory setting. Researchers are working on developing ultra-compact diode-pumped solid-state lasers to achieve system miniaturization and cost reduction. These lasers are anticipated to satisfy the optical lattice function requirements, such as those found in quantum clocks, the Raman-beam function in atom interferometers, and ion-trap quantum computers. The goal is to achieve a form factor suitable for integration into robust quantum instruments that can be used outside the laboratory.

Quantum devices are composed of substances like InSb, HgCdTe, and GaAs/AIGaAs. Due to the limited availability of these materials, they are initially more expensive than their conventional counterparts, and the photon absorption capacity of the device determines its sensitivity. Literature reveals that academic research focuses on nanofabrication and optical systems engineering to produce a miniature optical system for atom cooling that is the best in the world. This novel strategy is anticipated to generate a source of ultra-cold strontium atoms suitable for producing atomic time-reference standards with high precision. In addition, advancements in cooling technology could be used to create a quantum sensor, such as a quantum clock, that will serve as the beating heart of future network infrastructures and autonomous vehicles and provide a timing standard superior to that provided by GNSS. We conclude that the QST standard must be combined with size, weight, and power consumption reductions to enable field applications. Currently, the prototypes demonstrated in laboratory settings do not meet the requirements and scope necessary for most real-world QST applications.

B. FUTURE DIRECTIONS

Based on the results of RQ2, in this section, we reflect on the accumulated knowledge and discuss future directions for the usability of quantum sensors for system applications and various use cases. Using the quantum mechanical property of entanglement, quantum sensors containing entangled particles can measure environmental effects with extraordinary precision. Simulations of quantum entanglement have suggested enhancements in several areas, including coupling, durability, and returned fields. However, this work needs to be continued and extended in several directions, including improving density metrics, non-local or steerable states, pure states, and ensembles. We also encourage using mapping methods for continuous analyses of QST's current state and its potential real-world applications, while connecting QST to overall Quantum information systems research [126]. In the context of QST integration within the broader systems domain, further research must deal with QST integration with application infrastructure for distributed systems such as blockchain [for example [127]], DevOps processes [for example [128]], and artificial intelligence ecosystems [for example [129]].

Positioning and navigation services, as well as environmental detection, prediction, and modeling, are among the most promising applications where quantum sensors have the potential to improve current methods significantly. In the field of positioning and navigation services, we anticipate the integration of quantum accelerometers with conventional techniques, bridging traditional and quantum inertial navigation together. Combined with a quantum gravimeter and magnetometer, this technology could be the basis for quantum-enhanced navigation in subsea canyons, wavy seabeds, and coastal environments. However, substantial research is still required before quantum inertial navigation technology can be utilized in the real world. Even though the individual sensors required for quantum inertial navigation have been tested in laboratory settings, creating a quantum inertial measurement unit remains challenging.

Additional research is also required in the fields of network time synchronization and environmental detection, prediction, and modeling applications. The size, weight, and power consumption of quantum clocks and gyroscopes must be reduced. In particular, future research must demonstrate that a compact photonic integrated chip can replace the optical assembly in trapped atomic gyroscopes and clocks without degrading the device's performance. Despite the revolutionary potential of quantum imaging, it likely will take time before commercial products for environmental detection, prediction, and modeling become available.

VII. CONCLUSION

Quantum science is making significant progress, even though QST knowledge and application have not yet been made public. Hundreds of research papers are currently being published on various QST-related topics. It is astounding how many technologies, including NV centers, ions, photons, and quantum dots, are presently being developed in the QST space. In the past three years, there has been a discernible shift toward publishing more practical articles within the QST domain. Numerous qubit implementations, such as superconducting and trapped ions, are enhancing their fidelity. Google and Honeywell Quantum Systems made significant strides in 2021 by producing the first logical error-corrected qubits. Additionally, the advancements in the field of trapped ions were encouraging. This year, the world's first quantum atomic clock the size of a laptop will be installed on a British aircraft carrier to improve the positioning accuracy of the carrier [100].

This paper provides a thorough review that identifies, categorizes, and analyzes QST and its applications. We identified four basic sensing categories: quantum magnetometry and magnetoelectricity, quantum imaging and optics, quantum kinematics, and quantum timing. Each of these categories has the potential to generate entirely new commercial products for a variety of existing and novel implementations. Based on the review's findings, quantum magnetometry is the most advanced QST, accounting for 51.7% (30 out of 58) publications reporting on trials or demonstrations. In turn, quantum imaging and optics account for 25.86% of the cases (15 out of 58). Quantum timing and quantum kinetics in still in their initial phase of empirical validation. Besides, we discussed and offered four possible QST application categories for use in system research. They conclude with GPS-free positioning and navigation services, network time synchronization, underground and topological visibility detection, environment prediction, and modeling.

In addition, we discussed the challenges identified by researchers and practitioners in the field and provided an integrated perspective on the readiness of QST for implementing real-world applications and use cases. According to our analysis, there are two significant challenges. The first is the necessity to address increasingly complex real-world-focused problems, and the second is a comprehensive understanding of the QST's technical limitations. We anticipate that these challenges will stimulate research in the coming years.

In summary, we argue that applying QST to the four system domains is exciting. Even though QST is still in the early stages of practice, the continuous improvements to these technologies will encourage the community to implement more complex and realistic use cases, which in turn will introduce new unprecedented challenges that are currently unimaginable.

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