Quantum Sensing for the Cities of the Future

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Abstract

Quantum sensing technologies provide future cities with unimaginable techniques for solving their complex problems. Quantum sensors, through the utilization of quantum effects such as superposition, entanglement, and tunneling, can provide an unmatched level of sensitivity, precision, and durability against traditional sensing technologies. This study explores the potential applications of quantum sensing in four critical urban infrastructure domains: water, energy, transport, and construction. Throughout this study, we determine the most promising quantum sensing technologies for each domain. Besides, we discuss the technical progress of these sensors and the advantages they have in comparison with classical devices, as well as the organizational issues cities can face when implementing these sensors. Our results indicate that quantum sensing will be a critical enabler of future smart cities, generating advanced monitoring, control, and decision-making capabilities across various sectors. Nevertheless, taking advantage of this potential will demand the close partnership of cities, industry, academia, and policymakers to guide the complicated adoption process.

Keywords: Smart City, Future City, Sensor, Use Case, Infrastructure, Civil Engineering.

1. Introduction

The cities of the future will pose a multitude of challenges with the population explosion, the threat of natural disasters due to climate change, chronic shortage of resources, out-of-control waste, etc. When faced with such challenges, data-driven innovations are the basis for planning, deploying, and managing urban infrastructures and addressing the future cities' challenges (Berglund et al., 2020). Nevertheless, though permanent improvements in the existing sensors, the traditional technologies, mainly binary computational paradigms, will be inherently limited in their capabilities (Mishra et al., 2022; Puliafito et al., 2021; Pundir et al., 2022). Based on some fundamental concepts of quantum physics, a quantum sensor offers exceptional accuracy, sensitivity as well as robustness that all the classical sensors are never able to attain (Kantsepolsky, et al., 2023; Kop, et al., 2023). The objective of this research is to realize how quantum sensors can help solve the infrastructural problems of the city of the future to provide detailed forecasting, situational awareness, and informed management processes.

A sensor is a key technology allowing for basic scientific measurements. For many years, the information generated by sensors has been very important in situational awareness and informed decision-making processes. This study sought to reveal the potentially breakthrough capabilities that innovative quantum sensors with outstanding measurement sensitivity, accuracy, and robustness may offer to city planners and decision-makers in their efforts to address multi-faceted challenges of the future cities. Quantum technologies have become a new revolutionary power that offers large potential for urban environments development and city management reconceiving (Zhang, 2024). Quantum technologies such as quantum sensing, quantum security, and quantum computing adoption have attracted the attention of researchers, policymakers, and city administrators because these technologies can enhance resource allocation, sustainability, and resilience in urban environments (Purohit et al., 2023). Cities that are more and more conscious of the professional advantages that the merging quantum technologies bring into the city infrastructure and the city operations should resolve multiple organizational issues (Omrani et al., 2024; Nguyen, 2023). The adoption of quantum technology involves understanding the determinants of the organization's adoption behavior and the influence of transitioning from classical to quantum-based systems (Zheng, 2023).

When cities start to learn the process of quantum technologies integration, the role of literature review becomes dominant for finding out what different studies suggest so that organization problems are addressed properly and transformative potential of such technologies is utilized in urban environments. A critical overview of the present research context is designed to provide the reader with all the necessary data on the successful quantum technology integration variables in cities and signals of future research and practice directions soon to be popular in this dynamic field.

2. The Infrastructural Needs of the Future Cities

2.1 Civil Infrastructures - Energy

The population and economic activity growth will result in a significant increase in the energy demand. Maintaining a reliable and robust energy supply due to this growing demand constitutes a considerable challenge for the cities of the future. Cities must provide all residents equal opportunity for affordable energy, especially residents of poor areas (Kim et al., 2021). Creating and maintaining urban environments conducive to sustainable energy practices, adoption of renewable energy, and energy efficiency needs to be developed with the help of long-term planning, robust regulatory frameworks, effective energy policies, and professional' involvement (Razmjoo et al., 2022). Approaches for effective energy generation, demand control, and load distribution are the cornerstone of energy utilization. To cope with energy-related challenges, cities should establish energy infrastructure that may endure the effects of climate change, natural disasters, and other disruptions. The limitations of conventional sensing technologies pose many challenges across the energy-related landscape, while quantum sensing technologies have the potential to solve some of these challenges.

2.2 Civil Infrastructures - Transportation

Conventional transportation in urban areas creates congestion and produces greenhouse gases, noise, and air pollution, causing adverse effects on public health and the environment (Zhang et al., 2022; Yang et al., 2022). The need for the conversion to electric vehicles and clean fuels is critical for future cities. The development of charging infrastructure, intelligent transportation systems, and efficient multimodal transportation networks promotes the development of sustainable transportation options (Grace et al., 2023). Forming multimodal transportation requires seamless coupling between the different transportation elements, such as trains and buses, bicycles, and shared mobility services (Huang et al., 2022). Real-time traffic management is primarily dependent on the use of accurate and dependable real-time sensor data, which allows for making well-informed decisions (Kliestik et al., 2022). Sensors that have high reliability and real-time monitoring ability are very important to detect and warn of any potential safety concerns (Agarwal et al., 2022; Suseendran et al., 2022). Proper sensor data is crucial when dealing with the charge infrastructure management and clean transportation. Also, sensors are able to determine air quality and noise in urban locations thus, the data is used to evaluate and address health consequences of traffic (Jensen & Petrova, 2023).

2.3 Civil Infrastructures – Water Systems

Smart water management systems contribute to cities' resilience to adverse effects of climate change, such as droughts and extreme weather conditions, promote the efficient use of water resources, minimizing water scarcity and encouraging sustainable water management practices (Ler & Gourbesville, 2018; Owen, 2023). These systems enable timely intervention to ensure that residents are provided with safe and high-quality drinking water. The advanced sensing technologies and continuous real-time monitoring allow the decision-makers to track the water quality parameters and make timely interventions by optimizing the distribution of water and minimizing losses (Fu et al., 2022; Horita et al., 2023). When cities allow real-time data access and stimulate behavioral changes that together make citizens feel a sense of ownership and responsibility towards water resources, they ensure the availability of clean and safe water for the urban population (Fu et al., 2022; Owen, 2023). In turn, effective wastewater treatment systems also generate maximal treatment processes, therefore, saving energy and helping the efficiency of treatment (Choi et al., 2020; Mezni et al., 2022). Real-time sensors-based monitoring of wastewater parameters, which helps to determine the problems, including overload of pollutants and equipment malfunction, improves the efficiency and reliability of treatment. Through the application of smart water and wastewater management techniques, cities can mitigate the environmental degradation caused by water-associated activities such as lessening the level of pollution, preserving aquatic ecosystems, and ushering in sustainable water usage practices.

2.4 Civil Infrastructures - Construction

Many studies have recognized the role of automation in the improvement of efficiency and safety of construction projects. The utilities of the underground should be under close surveillance for a city to enhance planning and construction efficiency, maintenance and management of infrastructure, environmental protection, safety assurance, regulations compliance and preparedness, and responses to disasters (Grimaldi, 2019; Tanoli, 2019). Timely identification of the exact location of buried utilities is required for better planning and execution of construction projects, eliminating delays and extra costs due to unanticipated utility interferences or relocations (Vilventhan, 2021; Yadav, 2022). Moreover, observing underground utilities can help to recognize possible leaks or breaches in containment systems for hazardous materials like petroleum pipelines or chemical transport systems and to reveal and prevent leaks in water, gas, and sewage pipes (Ali, 2019; Alnahari, 2022). Early identification leads to timely repairs that prevent soil, ground, and surface water pollution. In addition to this, improved monitoring of underground electric and communication cables helps to locate areas of energy loss or inefficiency, which will make targeted maintenance and upgrade possible (Al-Bayati, 2020). However, the problem of the automated monitoring of construction sites remains very challenging (Cevikbas, 2022; Rao, 2022).

3. Introduction to Quantum Sensing

Quantum sensing bears many benefits compared to the conventional manner of sensing by promising to surpass the restrictions of the usual sensing methods (Vashist, 2023; Castelletto, 2023). Quantum sensors utilize the special characteristics of spin defects to attain enormous sensitivity and accuracy in signal detection (Jiang et al., 2023). Free electron quantum sensing of strongly coupled light-matter systems is an example of the ability of quantum technologies to provide measurements at the quantum scale (Karnieli et al., 2023). The spatial control of fluorescent colloidal nanodiamonds illustrates the flexibility of quantum sensors to achieve accurate and localized measurements (Vashist, 2023). The advancement of the solid-state single-photon sources at the infrared region is expected to improve the performance of quantum sensing applications (Castelletto, 2023).

Quantum sensing becomes a crucial element in ensuring the infrastructure's resilience and reliability, allowing for pre-emptive measures in response to possible safety issues and emergencies. Unsurprisingly that quantum sensing is foreseen as a revolutionary means for improving data collection, analysis, decision-making processes, and safety measures in urban environments (Bauer et al., 2021). In the next sections, we discuss the application of quantum sensing over four primary infrastructural domains of civil engineering.

3.1 Water and Wastewater Applications

Monitoring and controlling water is essential for the sustainability and efficiency of our water resources. Nevertheless, conventional sensing technologies face issues of sensitivity, resolution, and range that limit their efficiency in addressing the multi-dimensional challenges of the water sector (Kantsepolsky & Aviv, 2024). The introduction of quantum sensing technologies can eliminate these challenges and transform water monitoring and management practices. Ranging from groundwater exploration and subsurface water mapping to water body monitoring, pollution detection, and network management, these tools offer far-reaching progress that was unachievable with classic sensing techniques (Dasallas, 2024).

In groundwater evaluation and utilization systems, these technologies can improve aquifer assessment, recharge rate estimation, and optimization of well placement and pumping strategies, resulting in efficiency improvements (Kurizki et al.,

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2015). Moreover, these technologies are more effective in contamination detection and control, achieving detection limits down to parts per billion (ppb) levels (Kurizki et al., 2015). Quantum gravimeters represent one of the most promising technologies for water monitoring applications as they are sensitive enough to detect tiny differences in the gravitational field known to be related with water table levels. Quantum gravimeters are, like quantum magnetometers that sense changes in the magnetic field owing to the flow and features of groundwater, ten times more sensitive (1-10 fT/√Hz) and can be used up to 1000 meters deep, and hence are suitable for groundwater monitoring, subsurface water mapping, and fault detection in water networks (Heine et al., 2020). A sensitivity of 10^-12 m/s^2 and a spatial resolution between 1 and 5 meters are the typical characteristics of these gravimeters, and they are very important in groundwater assessments and subsurface water mapping (Heine et al., 2020).

Quantum cameras and multispectral sensors are also viewed as quantum sensing technologies with a great promise for the use in the water sector. These advanced sensors have significantly improved spatial resolution (0.5–2 m), greater depth penetration (to 50 m), and a larger spectral range (400–1100 nm), therefore can be used for water body mapping, shoreline monitoring, and water quality assessment (Dincer et al., 2019). In turn, quantum-enhanced spectrometers and hyperspectral sensors applied for water quality monitoring and contaminant identification, offer high sensitivity to parts per trillion (ppt), broad spectral range (200-2500 nm), and increased spectral resolution (1-10 nm) for detailed water quality assessment and pollution source tracking (Dincer et al., 2019).

In the field of water network management, quantum frequency sensors and acoustic leak detectors have appeared as the revolutionary technologies providing better precision (1-10 μm), greater stability (over 1000 hours), and improved sensitivity (1-10 dB) (Degen et al., 2017). Such developments enable improved detection, localization, and removal of leaks in water pipe networks. In fact, the use of quantum voltage sensors and smart water meters, which have high precision (0.1-1%), better resolution (0.1-1 L/min), and continuous data collection every 1-60 minutes, enhances the monitoring of water consumption and demand management (Awschalom et al., 2018). Examples of mapping the contribution of quantum sensing advances to urban water-related use cases are provided in Table 1.

Use-Cases	Technology Benefits	Technology Advancements	Sensor Types
Groundwater monitoring	Higher sensitivity and resolution	Enhanced groundwater assessment and contamination detection	Quantum gravimeters Quantum magnetometers
Subsurface water mapping	Higher sensitivity and wider range	Improved subsurface water mapping and aquifer characterization	Quantum magnetometers, Fluxgate magnetometers
Water pollution monitoring	Higher sensitivity and wider spectral range	Comprehensive water pollution analysis and source identification	Quantum-enhanced spectrometers, Hyperspectral sensors
Water network fault detection	Higher precision and improved stability	Improved fault detection and localization in water networks	Quantum frequency sensors, Acoustic leak detectors
Water consumption monitoring	Higher accuracy and resolution	Enhanced water consumption analysis and demand management	Quantum voltage sensors, Smart water meters

Table 1. Quantum sensing advances for water-related use cases

3.2 Transportation Applications

The challenges of transport in the urban environment are traffic congestion, safety, and environmental aspects. Conventional sensing and monitoring technologies mostly lack the precision, consistency, and real-time data required to address these problems. However, the quantum sensing system development promises to significantly change the methods of urban transportation management (Kantsepolsky & Aviv, 2024).

Utilizing quantum correlation principles, quantum radars and quantum lidars have the possibility to achieve super-sensitivity and super-resolution performance for delivering detection improvement and imaging resolution in environments where noise and interferences usually occur (Slepyan et al., 2022; Li et al., 2023). Quantum radar working in fog and rain improves safety of transportation (Li et al., 2023). Jahangir (2023) offers research on development of a networked photonic-enabled staring radar testbed for urban surveillance, focusing on the effect of phase noise in cluttered environment (Jahangir, 2023). This emphasizes the need for strong radar systems in the urban environment where clutter and noise may affect the signal detection. Quantum radars and lidars are considered by Slepyan et al. (2022) to have the possibility to achieve super-sensitivity and super-resolution with the help of quantum correlations (Slepyan et al., 2022). Quantum lidar is a sensing technology that possesses outstanding potential for urban applications. The quantum lidar has a maximum range of 1000 m and spatial resolution of 1–10 cm, making it possible to perform the accurate 3D mapping of urban infrastructure, road state, and movement of pedestrians (Ibáñez et al., 2018). It is an advanced technology that can be used in autonomous vehicle navigation, road maintenance scheduling, and urban traffic control, thus, demonstrating its applicability and its potential effect on the urban environment. The increase in signal-to-noise ratio by a factor of 10-100, and reduced noise susceptibility, make quantum lidar even more efficient in complex urban environments (Ibáñez et al., 2018).

Quantum gyroscopes' exceptional position accuracy within the range of 1 to 10 cm and orientation accuracy within 0.01 to 0.1 degrees can provide accurate vehicle positioning and orientation in urban areas, thus ensures stable navigation in tough environments like urban canyons and GPS-denied areas (Ozdemir et al., 2023). Considering the pronounced sensitivity of these systems noted at 10^-6 rad/s/√Hz and combined with long-term stability with a drift rate within the range of 0.001–0.01 degrees/hour, quantum gyroscopes can be applied in a variety of applications, including autonomous vehicle navigation, fleet tracking, and urban mapping (Ozdemir et al., 2023). The application of quantum inertia navigation systems and quantum gyroscopes in city transportation systems is an area that is full of the promise of significantly improving accuracy, reliability, and efficiency of navigation. They make smart cities and intelligent transportation networks possible by

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creating the safer and more efficient solutions for urban mobility.

Quantum magnetometers and quantum-enhanced GPS receivers have greatly improved vehicle locations and timing functions in urban areas. Jofre et al. (2023) state that quantum magnetometers are characterized by high sensitivity level (1-10 fT/√Hz) and a wide frequency range (up to 100 kHz), which enables accurate detecting local magnetic field variations caused by urban infrastructure. Moreover, the accuracy in location (1-10 cm) and timing (1-10 ns) of quantum-enhanced GPS receivers as well as higher reliability and signal immunity, making them indispensable for urban fleet management, traffic monitoring, and synchronization of intelligent transportation systems (Jofre et al., 2023). Examples of mapping the contribution of quantum sensing advances to transportation use cases are provided in Table 2.

Use-Cases	Technology Benefits	Technology Advancements	Sensor Types
Traffic monitoring and surveillance	Higher resolution and improved low-light performance	Enhanced traffic monitoring and incident detection	Quantum-enhanced cameras, Quantum radars and lidars
Vehicle navigation and positioning	Higher precision and reliability	Enhanced vehicle navigation and autonomous driving	Quantum gyroscopes, Quantum magnetometers, GPS receivers
Vehicle attitude determination	Higher accuracy and stability	Improved vehicle stability control and safety features	Quantum gyroscopes, Quantum magnetometers,
Micro-mobility & Rider safety	Higher accuracy and resolution	Enhanced obstacle detection and situational awareness	Accelerometers Gyroscopes Inertial measurement units

Table 2. Quantum sensing advances for transportation use cases

3.3 Energy Applications

Quantum sensor technologies have provided promise in the energy sector, specifically in cities, yielding high precision and sensitivity (Xia et al., 2023). These technologies can greatly improve energy real-time monitoring of energy consumption, grid performance, and renewable energy integration (Kantsepolsky & Aviv, 2024). Revolutionizing the measurement of electrical parameters with quantum-enhanced voltage and current sensors that have sensitivities of 1-10nV/√Hz for voltage and 1-10pA/√Hz for current enables developing mechanisms for the oversight of energy consumption, maintaining of the power quality, and the real-time tracking of dynamic load variations with a tremendous bandwidth from DC to 1 MHz (Metzler, 2023). In addition, the development of quantum technologies in the energy sector, it also promotes energy system and demand-side management research (Ferdian, 2023). With the help of renewable energy resources capabilities and through efficient size optimization approaches, integrated renewable energy systems are designed to ensure the best of efficiency and sustainability (Ferdian, 2023). Besides, buildings' lighting optimization and occupancy accuracy can be improved by applying quantum cameras and LiDARs devices.

Quantum technology utilization in the energy sector also stretches to energy storage alternatives, with quantum batteries in a special way (Theodoridou, 2023). Furthermore, quantum technologies used in urban energy management are expected to cause the development of innovative approaches aimed at optimizing energy systems, taking into account environmental effects and operational limitations (Gomaa & Emam, 2023). By using quantum principles, these batteries can improve storage capacities way too beyond so called efficient and sustainable energy management principles (Sharma et al., 2023). All these developments play a vital role in bettering functioning and reliability of energy systems with special regard to urban environment (Uzodinma et al., 2023). Xia et al. (2023) note that quantum batteries using entanglement and superposition have the capability to attain greater energy densities and rapid charging rates than those of conventional batteries. Theoretical energy densities over 1 MJ/kg and fast-charging times make quantum batteries promising to change the energy systems in urban environments, including in electric vehicles, renewable energy integration, and backup power systems (Xia et al., 2023).

The quantum-enabled energy applications also include demand response management and energy efficiency optimization in urban buildings and infrastructure (Metzler, 2023). Temperature, humidity, and gas sensors' precision and sensitivity can be utilized for buildings' energy efficiency and air quality. Quantum magnetometers with a sensitivity of 1-10 fT/√Hz and wide frequency bandwidths have found applications in power grid monitoring and fault detection. These sensors facilitates early anomaly detection and failure prediction, which helps in improving grid reliability and reducing downtime (Chugh et al., 2023). Going forward, quantum energy solutions development is in fast evolution towards uncertainties addressing and hybrid-electric propulsion systems optimization. Examples of mapping the contribution of quantum sensing advances to transportation use cases are provided in Table 3.

Use-Cases	Technology Benefits	Technology Advancements	Sensor Types
Power quality monitoring	Higher accuracy and wider bandwidth	Enhanced power quality analysis and fault detection	Quantum voltage sensors, Hall effect voltage sensors
Grid synchronization	Higher precision and improved stability	Improved grid stability and synchronization	Quantum frequency sensors, Digital frequency sensors
Temperature monitoring	Higher precision and sensitivity	Enhanced accuracy and range of measurements	Quantum dot thermometers, Fiber Bragg grating sensors
Gas detection	Improved selectivity and sensitivity	Comprehensive gas analysis and early detection	Quantum cascade lasers, Nanostructured metal oxide sensors
Humidity monitoring	Higher precision and wider range	Enhanced accuracy and coverage in diverse	Quantum dot humidity sensors, Capacitive

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		environments	humidity sensors

Table 3. Quantum sensing advances for energy use cases

3.4 Construction Applications

Urban construction is characterized by project complexity, safety issues, and resource utilization. The traditional methods of the construction sector are mainly based on manual activities and old-fashioned technologies, making them slow, costly, and producing poor results. Quantum sensing technology has the capacity to transform infrastructure development, improving the efficiency, safety, and sustainability at all stages of construction projects (Mijwil, 2023; Hao et al., 2023). In the construction planning stage, sensors are applied in site analysis, like in a subsurface condition analysis using ground-penetrating radar sensors (Comite et al., 2021) and accurately mapping of existing topography and infrastructure using LiDAR and gravimeters that can create accurate deep subsurface images. The sensitivity of quantum gravimeters that range from 1-10 μGal with a spatial resolution of 1-10 m provide details about structures, utilities, and soil conditions (Wu et al., 2019).

Once building has started, sensors remain essential. They inspect the worksite and operating environment of heavy equipment and machinery, thereby avoiding expensive repairs or structural failure (Son, 2019; Oke, 2021). The strain gauges, accelerometers, and displacement sensors are employed to monitor the quality of building works (Mazzei et al., 2023). These sensors can help in identifying emerging structural problems by supplying stress, deformation, and vibration data in real time. Strains down to 10^-12 and accelerations down to 10^-9 g can be easily sensed by these sensors, thus enabling early identification of structural distress, fatigue, and damage in buildings and infrastructure (Rottmann et al., 2023). Such sensors deliver an early warning of structural defects, thus allowing for prompt maintenance measures and minimizing the risk of critical damages in buildings and infrastructure. The real-time and long-term monitoring features of quantum sensors support the safety, reliability, and resilience of urban construction projects, ensuring the sustainability of assets and minimizing risks (Tang et al., 2023). Examples of mapping the contribution of quantum sensing advances to construction use cases are provided in Table 4.

Use-Cases	Technology Benefits	Technology Advancements	Sensor Types
Structural health monitoring	Higher sensitivity and resolution	Comprehensive structural analysis and early fault detection	Quantum-enhanced accelerometers, Fiber optic strain gauges
Vibration monitoring	Wider bandwidth and higher sensitivity	Enhanced vibration analysis and predictive maintenance	Quantum-enhanced accelerometers, MEMS accelerometers
Geophysical exploration	Higher sensitivity and resolution	Enhanced subsurface imaging and resource exploration	Quantum gravimeters, Superconducting gravimeters, Quantum magnetometers, Proton precession magnetometers
Spectroscopic analysis	Higher sensitivity and wider spectral range	Comprehensive material analysis and identification	Quantum-enhanced spectrometers, Fourier-transform infrared spectrometers
3D mapping and modeling	Extended range and higher resolution	Enhanced 3D mapping and object detection	Quantum-enhanced LiDARs, Time-of-flight cameras

Table 4. Quantum sensing advances for construction use cases

4. Discussion

The adoption of quantum technology by the cities is a complicated endeavor that encompasses different organizational issues. Several factors that have an influence on organizational adoption behavior have been explored by researchers and have provided an insight into the drivers and barriers of the advanced technologies implementation (Omrani et al., 2024). In this regard, cities have to take into account these aspects when customizing their quantum technology adoption strategies to realize advantages and surpass impediments.

Cities are presented with distinct opportunities and challenges as the classical sensing gives way to the quantum sensing (Zheng, 2023). The development of quantum sensing technologies is going to improve cities' abilities in the fields of infrastructure monitoring, energy management, transportation, and construction. When applied of a construction of objects, quantum gravimeters, and magnetometers allow for improved underground mapping (Heine et al., 2020). Traffic monitoring and vehicle navigation in complex urban environments can be enhanced by quantum radar and lidar systems (Slepyan et al., 2022). Metzler (2023) notes that quantum sensors provide more accurate measurements of power quality, grid synchronization, and demand response in energy.

Nevertheless, quantum sensing has quite a few critical issues. But, most quantum sensors have not achieved mass production, constraining widespread applicability. Quantum sensors are doubtful about their viability under various real-world scenarios. Operation of quantum sensors may be a complex process, which in turn, implies the need for training modules for civil engineers and city staff. The absence of uniform standards makes it challenging to compare and ensure that different types of quantum sensors are compatible with one another. Cities will also need to spend on knowledge and standards related to these emerging technologies.

Notwithstanding these temporary obstacles, quantum sensors will be more accessible, easy to use, and rugged in the not-so-far future. It will carry up their uptake in smart city applications. The creation of well-structured training courses and international standards will be crucial to maximize the opportunities for quantum sensing in urban environments. The development of the quantum sensing technologies, delay nature, of this research promotes a base for further discussion among scholar-practitioners regarding the potential and timeframe for implementing these sensors in core infrastructures of future cities. With critical literature review and synthesis of ideas in diverse studies, the cities can effectively navigate the quantum technology adoption process and maximize its enabling potential in urban landscapes. More research should focus on best practices in organizations, develop frameworks for the evaluation of quantum sensing performance, and forecast the timelines for scaled deployment across different sectors of infrastructure.

5. Conclusion

The quantum sensing technologies have great possibilities of changing the way cities will be monitoring and controlling the important infrastructures in such areas as water, energy, transportation, and construction. Utilizing quantum effects such as entanglement or superposition, these sensors can acquire sensitivity, precision, and functionality that is unattainable by classical instruments. Among the most advanced and promising quantum sensing technologies for smart city applications are quantum gravimeters, magnetometers, radar, and lidar systems.
Nonetheless, many challenges are still in translating quantum sensors from the laboratory environment to a real-world deployment at scale. Technical barriers are related to strength, standardization, and manufacturability of quantum sensors. The organizational blockers include developing knowledge, setting best practices, and rationalizing investment into these growing technologies. Collaboration between cities and industry, academia, and government stakeholders will be crucial in managing the intricate process of quantum technology adoption.

Despite these challenges, the direction is evident: Quantum sensing will play an important role for the smart cities of the future. With time, technologies will be developed and become more affordable, hence they will find applications in multiple infrastructure domains. Those cities that will engage with quantum sensing as part of their proactive approach today will be able to enjoy its advantages in the next decades.

To make this future a reality, several research priorities need to be followed. Quantitative techno-economic analysis and case studies are required to value the value proposition of quantum sensing with respect to particular smart city use cases. An empirical study on organizational best practices and challenges in the adaptation of quantum sensing technologies would be of great help. It is very important to have multidisciplinary frameworks and metrics, which would be used for the performance and compatibility evaluation of the heterogeneous quantum sensor networks. Roadmapping and foresight exercises can project the evolution path and scaling up of quantum sensing in diverse infrastructure sectors. In conclusion, policy research in relation to regulations, standards and public-private partnerships will play a significant role in promoting quantum sensing innovation and adoption.

This study makes a significant first attempt to lay down a techno-organizational infrastructure for quantum sensing to be used in future smart cities. Through synthesis of insights across disciplines and outlining major research needs, it seeks to generate more cross-sector collaboration in promoting these transformational technologies for urban sustainability and resilience. The race towards quantum sensing supremacy is here and cities should be at the forefront.

The authors declare that they have no conflict of interest.

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