Quantum Sensors for Enhanced Positioning and Navigation

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SUMMARY

Positioning, Navigation, and Timing (PNT) capabilities have become deeply integrated into the fabric of modern society, underpinning critical operations across a wide range of sectors. From transportation and telecommunications to meteorology and defence, the dependence on PNT systems continues to grow, primarily driven by evolving technologies and emerging applications. This reliance highlights the urgent need to advance PNT technologies to assure their resilience, reliability, and fitness for a broad range of uses. Modern PNT systems are fundamentally built around Global Navigation Satellite Systems (GNSS), supported by various ground-based and space-based augmentation systems. These satellite-based solutions have revolutionised PNT delivery and remain foundational to the expansion of PNT applications, however, their vulnerabilities are also well understood. Threats like interference (including jamming), spoofing, signal blockages, and system failures expose critical weaknesses. To address these challenges, a wide range of technologies and sensors, as alternative PNT solutions, have been developed. These include Low Earth Orbit (LEO) PNT systems, Inertial Navigation Systems (INS), natural PNT sources, terrestrial radio navigation systems, vision-based systems, and advanced cellular networks. Together, these technologies aim to enhance the robustness and adaptability of PNT services. In parallel, the ongoing second quantum revolution is poised to redefine the landscape of PNT. Quantum technologies, which leverage the principles of quantum physics, are transitioning from fundamental laboratory experiments to practical, real-world applications. This transformation introduces a wealth of opportunities for PNT through quantum sensing. The distinct advantages of quantum sensors include novel sensing modalities, compact design, low power consumption, and ultimate sensitivity limited only by the fundamental laws of physics. Collectively, these attributes position quantum technologies as potential game-changers for the future of PNT systems. However, despite its promise, the road to integrating quantum sensors into PNT applications is not without challenges. Quantum sensors, while exceptionally sensitive, are highly

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susceptible to interference from extraneous factors, which might masquerade as signals of interest. Furthermore, quantum entanglement, the most powerful quantum resource, is inherently fragile and difficult to maintain in practical environments. An additional restriction to some quantum implementations arises due to the utilisation of interferometry to extract signals. Interferometers are typically prone to phase wrapping issues, where signals can only be determined to modulo 2π. Finally, integrating quantum sensors with existing classical platforms presents additional hurdles due to their fundamental differences in operational principles, sensitivities, control requirements, as well as specifications. Therefore, achieving effective integration and seamless operation often demands extensive re-engineering and further adaptation. This presentation provides a comprehensive review of quantum sensors and their potential to address the limitations of current PNT systems. It explores the state-of-the-art in PNT systems, delves into the capabilities of quantum sensors, and examines their practical implementations in positioning and navigation. By doing so, we aim to illuminate the transformative potential of quantum sensing technologies and their role in shaping the future of PNT systems. This journey into the intersection of classical and quantum technologies sets the stage for a new era in resilient and advanced PNT solutions.