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QUANTUM-ENHANCED AUTONOMOUS NAVIGATION FOR DEEP SPACE: A FEASIBILITY STUDY ON ENTANGLEMENT-BASED POSITIONING AND ULTRA-PRECISION ORIENTATION SYSTEMS

Abstract

Deep-space navigation systems traditionally rely on Earth-based tracking, which introduces latency and limits autonomy due to communication delays. As missions venture farther, these limitations become increasingly restrictive. This paper proposes a quantum-based navigation model that leverages quantum entanglement and quantum gyroscopes to achieve ultra-precise, autonomous positioning without relying on Earth-based signals, addressing the constraints of conventional navigation methods. Traditional deep-space navigation depends on ground-based systems, causing significant delays and limiting operational flexibility. For missions exploring deep space, rapid, autonomous response capabilities are essential, as real-time communication with Earth becomes impractical. Quantum mechanics offers a promising solution: quantum entanglement enables instantaneous correlations between particle pairs across vast distances, while quantum gyroscopes can detect orientation changes with high precision. By integrating these quantum technologies, a navigation system can be designed to operate independently of Earth, enabling spacecraft to achieve real-time, self-contained navigation and significantly enhancing mission efficiency and capability. The proposed quantum navigation model integrates entangled particles and quantum gyroscopes for autonomous positioning and orientation. Entangled particle pairs are generated, with one particle remaining on Earth as a reference and the other traveling onboard the spacecraft. This setup allows real-time position adjustments via instantaneous correlation without direct communication. Quantum gyroscopes onboard the spacecraft detect minute orientation changes, enabling accurate navigation adjustments. Simulations were conducted to evaluate key performance metrics—accuracy, scalability, interference resilience, and feasibility—under conditions mimicking deep-space environments, including cosmic radiation and extreme temperature fluctuations. Simulation results indicate that quantum-based navigation achieves precise, real-time positioning and orientation independently of Earth-based systems, significantly enhancing spacecraft autonomy. This approach minimizes latency and reliance on Earth,

offering increased flexibility and responsiveness for deep-space missions. The feasibility of the model demonstrates its potential to improve efficiency and broaden the scope of space exploration. Future work will focus on improving quantum system resilience to withstand extreme space conditions, such as radiation and temperature variation. Expanding the model to support more complex applications, including multi-craft coordination and autonomous planetary landing, will be critical. With advancements in quantum technologies, integration with AI could enable fully autonomous, adaptive spacecraft capable of exploring the most remote regions of space. This research lays a foundation for future quantum-enabled deep-space exploration, promising unprecedented levels of precision and independence.