Course Title: Quantum Sensing and Navigation

Credit Hrs: 3

Prerequisites: Quantum Mechanics, Quantum Optics or Photonics, Classical Navigation and Sensing Systems, Electromagnetic Theory, UG-level Linear Algebra and Complex Vector Spaces

Course Overview:

This course provides an advanced study of quantum sensing and navigation systems. Students learn the fundamentals of classical sensing and navigation, including radar, LIDAR, inertial navigation, and precision measurement techniques. The course then introduces quantum-enhanced sensing methods using quantum states of light and matter, entanglement, and coherence. Applications include precision metrology, gravitational measurements, inertial navigation, and quantum gyroscopes. Emphasis is placed on theoretical derivations, simulation exercises, and practical considerations such as noise, decoherence, and environmental effects.

Course Objectives:

- Understand classical sensing and navigation principles and limitations.
- Master quantum-enhanced sensing techniques for navigation and precision measurement.
- Design and simulate quantum navigation and metrology systems.
- Analyze performance, error rates, and robustness under noise and decoherence.

Course Learning Outcomes (CLOs):

- Explain classical sensing and navigation principles, including accuracy and limitations.
- Apply quantum sensing techniques to enhance precision and sensitivity.
- Analyze entanglement and coherence-based quantum sensors for navigation applications.
- Evaluate the effects of decoherence, noise, and environmental factors on quantum navigation systems.
- Design and simulate quantum gyroscopes, accelerometers, and other navigation systems using medium-level derivations.

Course Week	Contents
1	Classical navigation and sensing fundamentals, including radar, LIDAR, and inertial systems. Range equations, SNR, detection probability, and limitations due to noise and sensor precision. Derivation: SNR and detection probability comparison across classical systems.
2	Inertial navigation systems (INS): accelerometers, gyroscopes, and sensor fusion techniques. Error accumulation, drift, and correction methods. Derivation: navigation error propagation and Kalman filter basics.
3	Classical precision measurement techniques: optical interferometry, atomic clocks, and frequency standards. Derivation: phase sensitivity and timing precision limits in classical interferometers.
4	Classical sensor signal processing: filtering, noise reduction, spectral analysis, and estimation theory. Derivation: optimal signal estimation and Cramér-Rao bounds for classical sensors.
5	Introduction to quantum sensing: qubits, superposition, coherence, and entanglement. Quantum vs classical limits in measurement precision. Derivation: standard quantum limit (SQL) and Heisenberg limit for parameter estimation.
6	Quantum interferometry: Mach-Zehnder and Ramsey interferometers, phase estimation using quantum states. Derivation: phase sensitivity and shot-noise-limited precision.
7	Midterm Exam – covering Weeks 1–6 (classical sensing and introductory quantum concepts).
8	Quantum-enhanced navigation: atomic clocks, optical clocks, and precision timing for navigation. Derivation: frequency stability, Allan variance, and clock synchronization.
9	Quantum gyroscopes and accelerometers: atom interferometry, Sagnac effect, and entangled matter-wave sensors. Derivation: phase accumulation and rotation rate sensitivity.
10	Quantum illumination and detection: entangled photon pairs for low-

reflectivity target detection, SNR improvement over classical sensors. Simulation exercises of target detection with quantum correlations.

11 Quantum-enhanced gravitational and inertial sensing: applications in navigation and geodesy. Derivation: sensitivity improvement using squeezed and entangled states.

12 Quantum sensor networks and cooperative navigation: distributed sensors, entanglement-assisted positioning, and error mitigation. Medium-level derivation: networked sensor fusion using quantum correlations.

13 Noise, decoherence, and practical limitations in quantum navigation systems. Simulation of environmental effects and strategies for robustness.

14 Advanced topics and emerging applications: hybrid classical-quantum navigation, quantum-enhanced LIDAR, and future trends in quantum metrology and navigation systems.

15 Project / Case Studies: Simulation and design of quantum navigation systems, atomic clock synchronization, and quantum gyroscope performance analysis.

16 Final Exam – covering Weeks 8–14 (full quantum sensing and navigation applications).

Textbooks / References:

- Degen, C. L., Reinhard, F., & Cappellaro, P. – *Quantum Sensing*, Rev. Mod. Phys., 2017.
- Giovannetti, V., Lloyd, S., & Maccone, L. – *Advances in Quantum Metrology*, Nat. Photonics, 2011.
- Budker, D., & Romalis, M. – *Optical Magnetometry*, Nat. Phys., 2007.
- Cronin, A. D., Schmiedmayer, J., & Pritchard, D. E. – *Atom Interferometers*, Rev. Mod. Phys., 2009.
- Mandel, L., & Wolf, E. – *Optical Coherence and Quantum Optics*, Cambridge University Press, 1995.
- Skolnik, M. – *Radar Handbook*, 3rd Edition, McGraw-Hill, 2008.

Assessments:

- Assignments: 10%
- Quizzes: 10%
- Midterm Exam: 30%
- Final Exam: 50%