Applied Quantum Sensing and Quantum Technologies

Credits: 6 (ECTS)

Course Coordinator: Assist. Prof. Dr. Mehmet Cengiz Onbaşlı, Koç University Physics and EE

Semester: 2022-2023 Fall

Contact Hours: 3 hours of online lecture per week (Tuesday, Thursday, 14:30-16:00)

Textbooks:

1) Ivan B. Djordjevic, *Quantum Communication, Quantum Networks and Quantum Sensing*, Academic Press, San Diego, USA, 2022

2) Isaac Chuang and Michael Nielsen. *Quantum Computation and Quantum Information*. Cambridge University Press, USA, 2011.

Required reading for the course:

1) C. L. Degen, F. Reinhard, P. Cappellaro, "Quantum sensing," Rev. Mod. Phys. **89** (3), 035002 (2017).

2) S. E. Crawford, et al., "Quantum Sensing for Energy Applications: Review and Perspective," Adv. Quantum Technol. **4**, 2100049 (2021).

3) G. Petrini, et al., Adv. Quantum Technol. **3**, 2000066 (2020).

4) Marco Barbieri, "Optical Quantum Metrology," PRX Quantum **3**, 010202 (2022).

5) S. Pirandola, et al., “Advanced in photonic quantum sensing,” Nat. Photon. **12**, 724-733 (2018).

6) S. Zhou, et al., "Achieving the Heisenberg limit in quantum metrology using quantum error correction," Nat. Commun. 9:78 (2018).

Catalog Description:

Review of linear algebra, differential equations, quantum mechanics, operators, and spins. Classical and microelectronic sensing concepts. Signal. Noise. Sensitivity. Noise types. Measurement uncertainty. Sampling. Analog-to-digital conversion. Modern sensing concepts and readout electronics. Discrete quantum states, superposition, entanglement. Quantum measurement protocols (Ramsey, echo and multipulse) and physical implementation examples. Quantum sensing for magnetic fields, electric fields, rotation, temperature and biosensing. Noise spectroscopy, dynamic range and adaptive sampling, ensemble sensing and auxiliary qubit sensors. Example sensing schemes beyond the standard quantum limit using entangled states (GHZ, N00N, squeezed states, W, and other types) to approach or reach the fundamental thermodynamic or Heisenberg uncertainty limits. Quantum sensor design and analysis paper and presentation.

Prerequisite(s): None
(Earlier exposure to quantum mechanics, operators, and instrumentation might be helpful.)
(Senior undergraduate, masters, or doctorate students are expected to take this course.)

Assessment Methods:

	Type	Label	Count	Total Contribution
1	Homework: Problem set/written		5	50
2	Midterm:Essay/written		1	25
3	Final:Essay/written and Presentation/oral		1	25

Minimum Requirements to Qualify for the Final Exam:
Completion of at least 3 homework assignments is required for qualifying for the final exam.

Course Learning Outcomes:

Course Learning Outcome	Assessment
At the end of the course students should be able to: • Establish a working knowledge of linear algebra, differential equations, Schrödinger’s equation, operator calculus and spins. • Understand the classical sensing concepts including signal, noise, sensitivity, noise types, measurement uncertainty, sampling, analog-to-digital conversion • Read and understand any electronic sensor datasheet and understand modern sensing concepts such as adaptive sampling, readout electronics, new materials • Identify the unique distinctions of quantum sensing from classical (microelectronic) sensing by referring to discretization, superposition, and entanglement of quantum states. • Describe the standard quantum measurement protocols to measure coherence times and quantum state stability (Ramsey, Hahn echo and multipulse) • Design physical implementation setups for each protocol for superconducting, trapped ion, silicon quantum dot, diamond nitrogen vacancy (NV) and other experimental quantum systems • Identify the operation principles of quantum sensors for magnetic field, electric field, rotation, temperature and biological species (i.e. virus, DNA strand, protein etc.) characteristics • Estimate quantum sensor metrics quantitatively (noise limit, dynamic range, signal-to-noise ratio and compare different quantum sensors	Homework: Problem set/written Midterm:Essay/written Final:Essay/written and Presentation/oral

• Propose and analyze advanced quantum sensing schemes using noise spectroscopy, dynamic range, adaptive sampling, and ensemble sensing • Describe how auxiliary qubits can assist in quantum sensing (extending the coherence time and serving as quantum memory, enabling quantum error correction) • Define and describe the standard quantum limit for sensing • Define special entangled states such as GHZ, N00N, squeezed states, W, and other types and describe how they are initialized • Analyze and describe how quantum sensing with standard entangled states (GHZ, N00N, squeezed states, W, and other types) might beat the standard quantum limit. • Design and analyze a quantum sensor and present its structure, operation principles, advantages, and disadvantages with respect to other sensors, propose and justify ways for improvement. • Written paper and oral presentation.	

Weekly Syllabus:

1. Review of linear algebra, differential equations, Schrödinger's equation, operator calculus and spins.

2. Classical sensing concepts including signal, noise, sensitivity, noise types, measurement uncertainty, sampling, analog-to-digital conversion

3. Overview and analysis of electronic sensor datasheets and modern sensing concepts such as adaptive sampling, readout electronics, new materials in sensors

4. Unique properties of quantum sensing: discretization, superposition, quantum entanglement

5. Standard quantum measurement protocols (Ramsey, Hahn echo and multipulse), quantum coherence times and quantum state stability

6. Design examples for experimental implementations of each protocol for superconducting, trapped ion, silicon quantum dot, diamond nitrogen vacancy (NV) quantum sensor systems

7. Operation principles of quantum sensors for magnetic field, electric field, rotation, temperature and biological species (i.e. virus, DNA strand, protein etc.) characteristics

8. Quantitative quantum sensor analysis (noise limit, dynamic range, signal-to-noise ratio) and comparison of different quantum sensors

9. Analysis of advanced quantum sensing schemes using noise spectroscopy, dynamic range, adaptive sampling, and ensemble sensing

10. Auxiliary qubits in quantum computation and sensing (extending the coherence time and serving as quantum memory, enabling quantum error correction)

11. The standard quantum limit for sensing

12. Definition, initialization, manipulation, and advantages of special entangled states (GHZ, N00N, squeezed states, W, and other types)

13. Analysis and description of how quantum sensing with standard entangled states (GHZ, N00N, squeezed states, W, and other types) might beat the standard quantum limit.

14. Quantum sensor design examples: structure, operation principles, comparisons with other sensors, and ways for improvement

ECTS - Workload Table:

Activities	**Number**	**Hours**	**Workload**
Course hours	14	3	42
Individual or group work	14	4	56
Homework	5	6	30
Midterm exam	1	2	4
Preparation for Midterm exam	2	15	30
Final exam	1	2	2
Preparation for Final exam	1	15	15
Total Workload:			179
Total Workload / 30:			179 / 30
			5.97
ECTS Credits of the Course:			6