Advanced Supervisory Modules for Atom Interferometric Measurement Systems

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Abstract- Atom interferometers translate inertial, gravitational, magnetic, timing, and field-gradient information into matter-wave phase and population readout. The same supervisory-control principle used for optical interferometers can be applied to cold-atom and atom-interferometric platforms by selecting objectives tied to inverse variance, Fisher information, fringe contrast, Dick-effect contribution, quantum projection noise, common-mode rejection, and sensitivity-function mismatch. This paper summarizes the math and science of ASCM concepts for matter-wave systems.

I. MATTER-WAVE MEASUREMENT MODEL

A light-pulse atom interferometer maps acceleration, rotation, gravity gradient, clock phase, magnetic field, or other measurands into an atomic phase. The detected population fraction can be idealized as a fringe

$$P(\phi) = 1/2\,[1 + C\cos(\phi + \phi_0)],\quad dP/d\phi = -C\sin(\phi + \phi_0)/2. \quad (1)$$

The phase estimator depends on contrast *C*, atom number *N*, detection efficiency, dead time, technical noise, and the chosen operating phase. A supervisory module should therefore optimize the measurement objective rather than merely hold a convenient fringe point.

II. CRAMER-RAO AND FISHER-INFORMATION OBJECTIVES

For an estimator of phase or acceleration, a natural objective is the inverse variance or a Fisher-information proxy. In a simple binomial population readout, the information available from the fringe depends on slope, contrast, and projection noise.

$$Var(\hat{\phi}) \geq 1/F(\phi),\quad J_{CRB}(\phi) = 1/Var(\hat{\phi}) \text{ approximately } F(\phi). \quad (2)$$

This makes an inverse-variance or information-stationary lock a matter-wave analogue of noise-stationary locking. The control parameter may be Raman phase, launch timing, interrogation time, trap depth, MOT loading time, magnetic-bias current, or a compensation waveform.

III. SUPERVISORY MODULE FAMILIES

- *Contrast-stationary lock:* regulates Raman phase or related phase controls toward high contrast and favorable fringe slope.
- *Inverse shot-noise variance lock:* adjusts MOT loading or detection timing to improve atom-number-limited precision.
- *Quantum projection-noise lock:* manages contrast, atom number, and readout conditions so projection noise remains the dominant modeled term.
- *Common-mode rejection lock:* maximizes cancellation between paired interferometers or gradiometer arms.
- *Sensitivity-function lock:* matches pulse areas, timing, and response functions to reduce vibration or aliasing sensitivity.
- *Dick-effect lock:* adjusts dead time, cycle timing, or interrogation scheduling to reduce aliasing of oscillator or vibration noise.

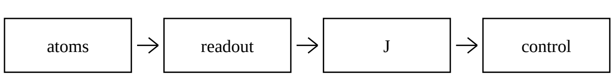

Fig. 1. Matter-wave supervisory module path.

IV. HYBRID AND COMMERCIAL PLATFORM RELEVANCE

The rendered atomic-interferometry draft emphasizes that platform-specific objectives can be mapped onto a common ASCM skeleton: compute a real-time scalar functional, perturb a control parameter, estimate slope or gradient, and update the control value while respecting protected analysis bands and experimental dead time.

For cold-atom clocks, gravimeters, gradiometers, gyroscopes, and atom-chip systems, the hardware constraints differ from optical interferometers, but the supervisory question is the same: which operating point maximizes useful measurement information after practical noise, loss, timing, and readout constraints are included?

V. VALIDATION PATH

- *Fringe map:* sweep Raman phase or equivalent phase and estimate contrast, slope, and detection variance.
- *Objective map:* compute inverse variance, Fisher proxy, common-mode rejection, or sensitivity-function mismatch across control settings.
- *Stationary lock:* apply a small protected perturbation and close a low-bandwidth supervisory loop.
- *Comparative test:* compare Allan deviation, phase variance, dead-time sensitivity, or gradiometer rejection with and without the module.

VI. TECHNICAL SIGNIFICANCE

The atom-interferometry module concept treats quantum sensor operation as a performance-functional control problem. Rather than locking only to fringe position or hardware convenience, the instrument can be supervised by objectives tied to estimator variance and accessible information. This creates a common mathematical framework across optical and matter-wave sensing platforms.

REFERENCES

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