Objective-Function Supervisory Control Modules for Interferometric Measurement Systems

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Abstract- Advanced Supervisory Control Modules (ASCMs) generalize the NSL concept from a specific normalized noise objective to a broader class of performance functionals. A supervisory layer obtains detector data, computes a scalar objective associated with measurement performance, perturbs an operating-point control parameter, estimates a local slope or gradient component, and updates a setpoint or actuator command toward a stationary operating point. The approach is intended to operate above, beside, or in combination with conventional inner locks.

I. GENERALIZED CONTROL STATEMENT

An interferometric apparatus often already has an inner lock: a PDH lock, PID loop, dither lock, phase lock, resonance lock, bias lock, or similar stabilizer. The ASCM concept adds a slower supervisory loop that does not replace the inner lock. Instead, it adjusts the setpoint, bias, detuning, local-oscillator phase, dark-port phase, squeezing angle, or other command according to a measured performance functional.

$$J = J[y_1(t), y_2(t), ..., delta, theta, g]. \quad (1)$$

The functional J may be a detection-normalized noise objective, measured variance, band-integrated spectral density, estimator-variance proxy, Fisher-information proxy, accessible-information proxy, correlation metric, matched-filter metric, residual-noise metric, or a weighted combination.

II. STATIONARY OPERATING POINT

$$J(delta_0 + Delta\_delta) \sim= J(delta_0) + (dJ/ddelta)|_{delta0}\, Delta\_delta + 1/2(d^2J/ddelta^2)|_{delta0}\, Delta\_delta^2. \quad (2)$$

At a stationary operating point where *dJ/ddelta* is reduced toward zero, first-order conversion of operating-point fluctuations into objective excursions is suppressed. The remaining sensitivity depends on curvature, disturbance amplitude, estimator variance, and loop bandwidth.

III. PERTURBATION AND SLOPE ESTIMATION

The perturbation may be sinusoidal, multi-tone, coded, pseudo-random, chirped, stepped, or swept. Slope extraction may be performed by lock-in detection, synchronous demodulation, correlation, matched filtering, finite-difference estimation, regression, stochastic approximation, extremum-seeking control, or model-based estimation.

$$delta_{cmd}(t) = delta_0(t) + A_d \sin(2\, pi\, f_d\, t),\ e(t) \text{ proportional to } dJ/ddelta. \quad (3)$$

detector → J(delta) → slope → setpoint

Fig. 1. Supervisory objective-function loop.

IV. PROTECTED MEASUREMENT BAND

The protected measurement band is the band used for sensing, signal recovery, or performance-functional estimation. Supervisory perturbations should be placed outside this band or structured so that they can be separated by demodulation or code correlation. This protects the measurement while still providing the local information needed for objective-function control.

V. MODULE ARCHITECTURE

- *Inner lock:* provides capture and high-bandwidth stabilization.
- *Functional estimator:* computes J from one or more detector channels.
- *Slope estimator:* compares J to a perturbation reference or finite-difference schedule.
- *Supervisor:* updates a setpoint, offset, bias, phase, or actuator command.
- *Monitor/recovery state:* detects mislock, threshold violation, or loss of convergence.

VI. TECHNICAL SIGNIFICANCE

The ASCM framing separates the optical instrument from the performance objective. A conventional lock may hold the instrument in a convenient optical state, while the supervisory layer asks whether that state is optimal for the measurement being performed. This makes the control layer adaptable to classical, coherent, integrated-photonic, and quantum-enhanced instruments.

REFERENCES

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