Abstract

Quantum entanglement can enhance the sensitivity of atomic sensors to static or slowly varying fields. But many important applications in fields such as medicine or navigation require tracking fast or transient signals. This presents unique challenges, one of them being that the potential benefits of entanglement in such cases are still not fully understood. To investigate this, we apply concepts from continuous quantum measurements and estimation theory to optical atomic magnetometers, aiming to accurately model these devices, interpret their measurement data, control their dynamics, and achieve optimal sensitivity.

Quantifying this optimal performance requires determining a fundamental quantum limit on sensitivity. The above bound imposed by noise is derived and shown to scale at best linearly with the sensing time and number of atoms N, ruling out any super-classical scaling. Moreover, this quantum limit is independent of the initial state, measurement, estimator, and measurement-based feedback, and depends only on the decoherence model and strength of the field fluctuations. Thus, finding an estimator that attains this limit proves a given sensing strategy optimal.

To approach this bound, we develop a quantum dynamical model scalable w.r.t. N, based on a co-moving Gaussian approximation of the stochastic master equation, which includes both measurement backaction and decoherence. This enables the construction of a real-time estimation and control architecture that integrates an extended Kalman filter (EKF) with a linear quadratic regulator (LQR).

By simulating the magnetometer with our model and our proposed EKF+LQR strategy, we show that quantum-limited tracking of constant and fluctuating fields is within reach of current atomic magnetometers. Strikingly, our sensing strategy can also track biological relevant signals, such as heartbeat-like waveforms. It can furthermore be used to drive the atomic ensemble into an entangled state, even when the measurement record is used for feedback but afterwards discarded.