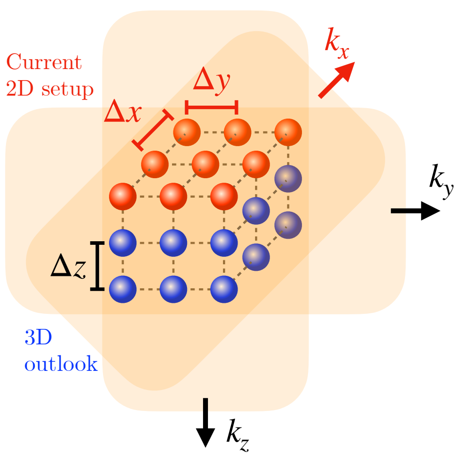
Multi-axis atom interferometry for inertial sensing and navigation

C. Struckmann,* K. Stolzenberg, E. M. Rasel, D. Schlippert, and N. Gaaloul
Leibniz Universität Hannover, Institut für Quantenoptik,
Welfengarten 1, 30167 Hannover, Germany
(Dated: July 12, 2024)

Quantum sensors based on the interference of matter waves provide a highly sensitive and stable measurement tool for inertial forces with applications in geodesy, navigation, or fundamental physics. Conventional atom interferometers, however, can only measure inertial forces along a single axis, yielding information about one acceleration and one rotation component. To fully characterize the motion of a moving body, an inertial measurement unit must capture the acceleration and rotation along three perpendicular directions. Extending this atom interferometric measurement scheme to multiple components would normally require subsequent measurements along a differently oriented axis.

In this contribution, we present a novel method to operate a quantum sensor based on a 2D array of Bose-Einstein Condensates enabling multi-axis sensing through simultaneously operated single-axis atom interferometers [1]. By differentially inferring rotational components, making use of common mode rejection, we target shot-noise-limited sensitivities. Such a scheme and its generalization to 3D arrays offer a significant sensitivity boost for 3D space-borne inertial navigation. We detail the multi-dimensional scaling of the inertial phases as well as the capabilities of such a multi-axis measurement unit.

This work is supported by DLR funds from the BMWi (50WM2263A-CARIOQA-GE and 50WM2253A-(AI)ˆ2).



Measurable inertial quantities

Linear acceleration

$$\mathbf{a} = \begin{array}{c} \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} \end{array} \begin{array}{l} k_x \\ k_y \\ k_z \end{array}$$

Linear acc. gradient

$$\hat{\Gamma} = \begin{array}{c} \begin{array}{ccc} \Delta x & \Delta y & \Delta z \end{array} \\ \begin{pmatrix} \frac{\partial a_x}{\partial x} & \frac{\partial a_x}{\partial y} & \frac{\partial a_x}{\partial z} \\ \frac{\partial a_y}{\partial x} & \frac{\partial a_y}{\partial y} & \frac{\partial a_y}{\partial z} \\ \frac{\partial a_z}{\partial x} & \frac{\partial a_z}{\partial y} & \frac{\partial a_z}{\partial z} \end{pmatrix} \end{array} \begin{array}{l} \\ k_x \\ k_y \\ k_z \end{array}$$

Angular velocity

$$(\hat{\Omega})^2 = \begin{array}{c} \begin{array}{ccc} \Delta x & \Delta y & \Delta z \end{array} \\ \begin{pmatrix} -\Omega_y^2 - \Omega_z^2 & \Omega_x\Omega_y & \Omega_x\Omega_z \\ \Omega_x\Omega_y & -\Omega_x^2 - \Omega_z^2 & \Omega_y\Omega_z \\ \Omega_x\Omega_z & \Omega_y\Omega_z & -\Omega_x^2 - \Omega_y^2 \end{pmatrix} \end{array} \begin{array}{l} \\ k_x \\ k_y \\ k_z \end{array}$$

Angular acceleration

$$\dot{\hat{\Omega}} = \begin{array}{c} \begin{array}{ccc} \Delta x & \Delta y & \Delta z \end{array} \\ \begin{pmatrix} 0 & -\dot{\Omega}_z & \dot{\Omega}_y \\ \dot{\Omega}_z & 0 & -\dot{\Omega}_x \\ -\dot{\Omega}_y & \dot{\Omega}_x & 0 \end{pmatrix} \end{array} \begin{array}{l} \\ k_x \\ k_y \\ k_z \end{array}$$

Schematic of the multi-axis quantum inertial sensor under consideration.
The current 2D setup (red, left image) is able to retrieve information about the components marked in red on the right. Here, we demonstrate the measurement of a_x, Ω_z and $\dot{\Omega}_z$ and give an outlook to the capabilities of a 3D array (blue, left image).

[1] K. Stolzenberg, C. Struckmann, S. Bode, R. Li, A. Herbst, V. Vollenkemper, D. Thomas, E. M. Rasel, N. Gaaloul, and D. Schlippert, (2024), arXiv:2403.08762 [physics.atom-ph].

* struckmann@iqo.uni-hannover.de