Using Computer Vision for Analysis of Collapsed Bose-Einstein Condensate in Dual Sagnac Interferometer

CS4991 Capstone Report, 2024

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ABSTRACT

Efficiently being able to accurately record changes in orientation is integral to the success of high-altitude navigation, where satellite navigation systems such as GPS have sparse coverage [5]. This report presents a method for predicting the angle of deflection in a Bose-Einstein condensate (BEC) atom interferometer gyroscope (AIG) using principal component analysis (PCA) and machine learning on images of the collapsed BEC. The proposed solution involves applying PCA to extract basis images, using multivariate linear regression to determine an optimal linear combination of these basis images, and correlating the dot product of this optimal basis image with the collapsed BEC image data and the gyroscope's angle of deflection. Results demonstrate the feasibility of this approach for predicting gyroscopic angles from BEC interferometry images. Future work is needed in generalizing results to larger datasets and exploring methods to further fine-tuning angle prediction.

1. INTRODUCTION

Bose-Einstein condensates (BECs) are a state of matter in which a dilute gas of bosons is cooled to temperatures near absolute zero, causing a large fraction of the atoms to occupy the lowest quantum state [2]. BECs have unique properties that make them useful for various applications, including atom interferometry. In an atom interferometer, a BEC is split into two or more coherent matter waves that follow different paths before recombining, causing interference patterns that can be used to measure properties such as rotation [1].

1.1 Motivation

BEC atom interferometer gyroscopes offer a promising alternative to conventional gyroscopes for high altitude and deep space navigation. In high altitude missions, spacecraft must rely on alternative methods for determining their orientation and position, as the signals from Earth-based navigation satellites become weaker and less reliable with increasing distance [5].

By leveraging the unique properties of Bose-Einstein condensates and the high sensitivity of atom interferometry, these gyroscopes have the potential to provide unprecedented accuracy and stability over long durations [4]. The development of compact, robust, and high-performance BEC atom interferometer gyroscopes could enable more precise spacecraft orientation determination and trajectory control, enhancing the capabilities of deep space exploration missions.

2. RELATED WORKS

Segal, et al. [8] demonstrated the utility of PCA and independent component analysis (ICA) for extracting useful data from images of a BEC experiment. They applied these techniques to rapidly determine the differential phase of a BEC interferometer from large sets of images of interference patterns. Their work showed that PCA could be used to rank the significance of principal components in the images, allowing for the identification of the component corresponding to the interferometer phase signal. By examining the principal components, the authors were able to identify the two dominant noise processes in the data: fluctuations in the total number of atoms and fluctuations in the vertical position of the atoms during imaging.

At the UVA cold atom lab, Horne and Sackett [7] have demonstrated a new variant of BEC atom interferometers, which provides a weak, cylindrically symmetric magnetic trap to support the atoms against gravity. This trapping configuration is advantageous because it is relatively compact and hence possesses a wider range of applications as a gyroscope. The authors proposed several potential applications of this trapping configuration for rotation sensing, including a dual-interferometer scheme in which the BEC would be split and guided along a circular path using Bragg pulses, forming a closed-loop interferometer sensitive to rotations. A continuing work at the cold atom lab has since realized this very experiment [3].

3. PROJECT DESIGN

The image data used in this report is procured from the Dual Sagnac Interferometer (DSI) developed by the UVA cold atom lab. In their experiment, a BEC is split apart and moved in opposite directions along a circular path as outlined by Horne, et al. As the split BEC moves, the platform containing the interferometer is rotated. The split BECs then become out of phase and interfere deconstructively when recombined. They then take an absorption image, collapsing the BEC and capturing the corresponding distribution of the atoms [3].

3.1 Problem

The main problem addressed in my experiment was using machine vision to predict how much the internal chamber of cylindrical AIG had been rotated given an image of the collapsed BEC. A training dataset consisting of a few hundred images of the collapsed BEC state as well as the corresponding angles at which the apparatus had been rotated was provided to me courtesy of the UVA cold atom lab. To uncover this relation I applied the noise reduction methods of Segal et al. by using PCA and then performed multivariate regression on the principal components to find a single basis image which maximally explained the correlation between the interference inferred by the distribution in the images and the angles at which the apparatus was deflected.

3.2 Principal Component Analysis

Principal component analysis is a technique for reducing the dimensionality of a dataset by identifying the principal components (or basis images) that capture the most variance in the data [6]. In the context of our data, by analyzing the basis images we can visualize the characteristic ways in which the distributions differ and then later relate those differences to the rotation of the apparatus. In particular, the absorption images show that the majority of the BEC is congregated into three piles (see fig. 1.1). The four principal components that explain the greatest variance in our data are shown in fig. 1.1-4.

In accordance with Segal, et al. the first and second principal components indicate that most of the variance present in the images is derived from the inconsistent size of the BEC and small vertical deviations in where the condensate is centered. The third and fourth basis images, however, both appear to contain information regarding the relative size of the

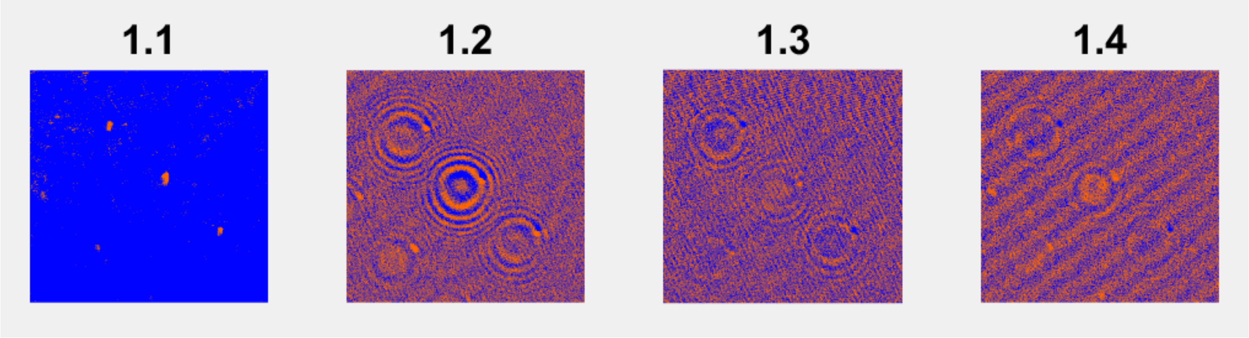

Figure 1. Four principal components for the collapsed BEC training data represented as basis images in order of decreasing variance from left to right

three piles. This poses a problem because the relative size of the piles is what we planned to correlate to the angle of deflection.

3.3 Machine Learning

To solve the issue of multiple basis images containing information relevant to determining the angle of deflection, we employed the use of machine learning. To do this we multiply each basis image by a unique scale factor and then add them together to create a single basis image for our prediction. Taking the dot product between our basis image and a new image then gives us a score which can be correlated to the angle of deflection. To determine the unique scale factors for each basis image we allow them to be the free parameters in a multivariate linear regression. We then used the standard gradient descent algorithm to maximize the scores of our images in the training data with their respective angles. The result is a single image that maximally extracts the relevant information for determining the angle of deflection.

4. RESULTS

By using the optimal basis image acquired from the multivariate regression we generated scores for a large representative sample of the data. We then used a linear model to predict the angle of deflection from the scores shown in fig. 2.

By applying our model to the training data we were able to achieve a .92 correlation between the BEC images and the angle of deflection. Thus, the coefficient of determination is .84, meaning that 84% of the variability in the angle of deflection can be explained by our model (fig. 2.).

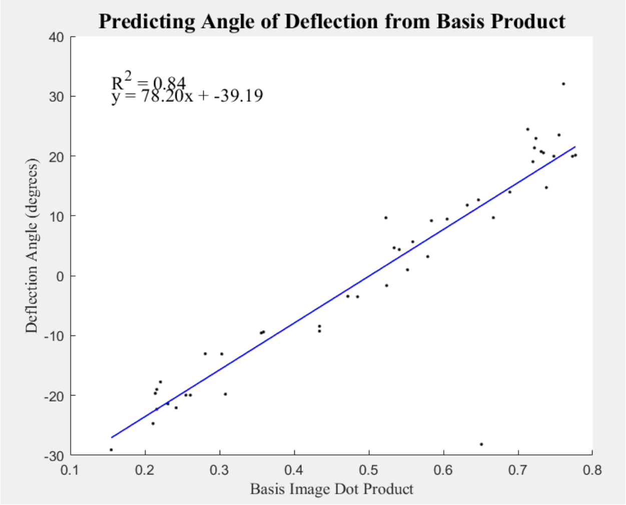

Figure 2. Linear correlation between the interferometer's angle of deflection and the score calculated by taking the dot product with the optimal basis image

5. CONCLUSION

This project serves as an early work in establishing the viability of using absorption images for extracting information from the cold atom lab's DSI for use as an AIG. The results demonstrated in fig. 2. show that PCA and linear regression might serve as a plausible method for retrieving low resolution information from such images. However, the .91 correlation coefficient is relatively weak given the highly accurate readings the DSI is designed for. Hence, it is unlikely that the results given in this experiment are sufficient to generate gyroscopic readings with a sensitivity competitive with state-of-the-art techniques. Applying PCA directly to the absorption images remains an important step in demonstrating feasibility and justifying the employment of more sophisticated and costly machine learning techniques.

6. FUTURE WORK

An important next step in continuing this work will be to apply other common computer vision techniques to analyze the images. In particular, a deep learning algorithm such as a convolution neural network (CNN) might be a viable method for extracting more information from the training dataset since CNNs are designed to learn invariances and abstract characteristics of local data from images. Beyond this, expanding the training dataset to include more samples and higher resolution images should be considered to boost the overall quality of data these models are trained on.

7. ACKNOWLEDGMENTS

Special thanks should be given to Prof. Cass Sackett for giving me this project idea, allowing me to work alongside him at the UVA cold atom lab, and providing me with the training data and related works. The skills and knowledge gained from this experience have been invaluable.

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