ORIGINAL PAPER

Robust Bayesian functional principal component analysis

Jiarui Zhang[1] · Jiguo Cao[1] · Liangliang Wang[1]

Abstract

We develop a robust Bayesian functional principal component analysis (RB–FPCA) method that utilizes the skew elliptical class of distributions to model functional data, which are observed over a continuous domain. This approach effectively captures the primary sources of variation among curves, even in the presence of outliers, and provides a more robust and accurate estimation of the covariance function and principal components. The proposed method can also handle sparse functional data, where only a few observations per curve are available. We employ annealed sequential Monte Carlo for posterior inference, which offers several advantages over conventional Markov chain Monte Carlo algorithms. To evaluate the performance of our proposed model, we conduct simulation studies, comparing it with well-known frequentist and conventional Bayesian methods. The results show that our method outperforms existing approaches in the presence of outliers and performs competitively in outlier-free datasets. Finally, we demonstrate the effectiveness of our method by applying it to environmental and biological data to identify outlying functional observations. The implementation of our proposed method and applications are available at https://github.com/SFU-Stat-ML/RBFPCA.

Keywords Functional data analysis · Robust estimation · Sparse functional data · Multivariate skew elliptical distribution · Model comparison · Outlier detection

1 Introduction

The development of modern technology has resulted in the continuous recording of data during a given period in many scientific fields, such as neuroscience, biology, and environmental science. These data can be categorized as functional data (Ramsay and Silverman 2005b; Ferraty and Vieu 2006; Horváth and Kokoszka 2012; Hsing and Eubank 2015), which are usually observed over time, space or any other continuous domain. For instance, Fig. 1 displays two examples of functional data. Figure 1a shows a collection of densely observed trajectories from the Hawaii Ocean Oxygen dataset (HOT-DOGS 2022), wherein certain outlying trajectories have been highlighted. Figure 1b presents one illustration of

sparse function data from the CD4 dataset (Zeger and Diggle 1994), with only a few observations per curve. Both datasets have a few curves demonstrating unusual patterns in contrast to the rest.

Functional principal component analysis (FPCA) plays a crucial role in functional data analysis (FDA) as a dimension reduction technique. FPCA can be viewed as an exploratory analysis tool to discover the hidden structure of the data by capturing the optimal low-dimensional representation and the major source of variations among curves. FPCA can also be used to help reconstruct partially observed functions or used as a preprocessing step for regression analysis (Reiss et al. 2017) or clustering tasks (Margaritella et al. 2021). The frequentist analysis of FPCA is a mature field. Numerous works have been proposed to explore fully or densely observed function data (Dauxois et al. 1982; Rice and Silverman 1991; Cardot 2000; Hall and Hosseini-Nasab 2006). Studies of the FPCA approach for sparsely observed data, a more challenging situation, can also be seen in James et al. (2000), Yao et al. (2005), and Paul and Peng (2009). Wang et al. (2016) provided a detailed review of methods, open questions and applications of FPCA.

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