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Sliced Inverse Regression for datastreams: 
An introduction

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Abstract
In this tutorial, we focus on data arriving sequentially by block in 
a stream. A semiparametric regression model involving a common EDR 
(Effective Dimension Reduction) direction \( \beta \) is assumed in each block. Our 
goal is to estimate this direction at each arrival of a new block. A simple 
direct approach consists of pooling all the observed blocks and estimating 
the EDR direction by the SIR (Sliced Inverse Regression) method. But in 
practice, some disadvantages become apparent such as the storage of the 
blocks and the running time for high dimensional data. To overcome these 
drawbacks, we propose an adaptive SIR estimator of \( \beta \). The proposed 
approach is faster both in terms of computational complexity and running 
time, and provides data storage benefits. A graphical tool is provided in 
order to detect changes in the underlying model such as a drift in the 
EDR direction or aberrant blocks in the data stream. This is a joint work 
with Marie Chavent, Vanessa Kuentz-Simonet, Benoît Liquet, Thi Mong 
Ngoc Nguyen and Jérôme Saracco.

1 Sliced Inverse Regression (SIR)

1.1 Multivariate regression
Let \( Y \in \mathbb{R} \) and \( X \in \mathbb{R}^p \). The goal is to estimate \( G : \mathbb{R}^p \to \mathbb{R} \) such that 
\[
Y = G(X) + \xi 
\]
where \( \xi \) is independent of \( X \).

- Unrealistic when \( p \) is large (curse of dimensionality).

- **Dimension reduction**: Replace \( X \) by its projection on a subspace of 
lower dimension without loss of information on the distribution of \( Y \) given 
\( X \).

- **Central subspace**: smallest subspace \( S \) such that, conditionally on the 
projection of \( X \) on \( S \), \( Y \) and \( X \) are independent.
1.2 Dimension reduction

- Assume (for the sake of simplicity) that \(\dim(S) = 1\) i.e. \(S = \text{span}(b)\), with \(b \in \mathbb{R}^p\) \(\implies\) **Single index model:**

\[
Y = g(<b, X>) + \xi
\]

where \(\xi\) is independent of \(X\).

- The estimation of the \(p\)-variate function \(G\) is replaced by the estimation of the univariate function \(g\) and of the direction \(b\).

- **Goal of SIR** [Li, 1991] : Estimate a basis of the central subspace. (\textit{i.e.} \(b\) in this particular case.)

1.3 SIR

**Idea:**

- Find the direction \(b\) such that \(<b, X>\) best explains \(Y\).
- Conversely, when \(Y\) is fixed, \(<b, X>\) should not vary.
- Find the direction \(b\) minimizing the variations of \(<b, X>\) given \(Y\).

**In practice:**

- The support of \(Y\) is divided into \(h\) slices \(S_j\).
- **Minimization of the within-slice variance of** \(<b, X>\) **under the constraint** \(\text{var}(<b, X>) = 1\).
- Equivalent to **maximizing the between-slice variance** under the same constraint.
1.4 Illustration

1.5 Estimation procedure

Given a sample \{((X_1, Y_1), \ldots, (X_n, Y_n))\}, the direction \( b \) is estimated by

\[
\hat{b} = \arg\max_b b' \hat{\Gamma} b \quad \text{such that} \quad b' \hat{\Sigma} b = 1.
\] (1)

where \( \hat{\Sigma} \) is the empirical covariance matrix and \( \hat{\Gamma} \) is the between-slice covariance matrix defined by

\[
\hat{\Gamma} = \sum_{j=1}^{h} \frac{n_j}{n} (\bar{X}_j - \bar{X}) (\bar{X}_j - \bar{X})', \quad \bar{X}_j = \frac{1}{n_j} \sum_{Y_i \in S_j} X_i,
\]

where \( n_j \) is the number of observations in the slice \( S_j \).

The optimization problem (1) has a closed-form solution: \( \hat{b} \) is the eigenvector of \( \hat{\Sigma}^{-1} \hat{\Gamma} \) associated to the largest eigenvalue.

1.6 Illustration

Simulated data.

- Sample \{((X_1, Y_1), \ldots, (X_n, Y_n))\} of size \( n = 100 \) with \( X_i \in \mathbb{R}^p \), dimension \( p = 10 \) and \( Y_i \in \mathbb{R}, i = 1, \ldots, n \).
- \( X_i \sim \mathcal{N}_p(0, \Sigma) \) where \( \Sigma = Q \Delta Q' \) with
  - \( \Delta = \text{diag}(p^2, \ldots, 2^2, 1^2) \),
$Q$ is an orientation matrix drawn from the uniform distribution on the set of orthogonal matrices.

- $Y_i = g(<b, X_i>) + \xi_i$ where
  - $g$ is the link function $g(t) = \sin(\pi t/2)$,
  - $b$ is the true direction $b = 5^{-1/2} Q(1, 1, 1, 1, 0, \ldots, 0)'$,
  - $\xi \sim \mathcal{N}_1(0, 9.10^{-4})$

2 SIR for data streams

2.1 Context

- We consider data arriving sequentially by blocks in a stream.
- Each data block $t = 1, \ldots, T$ is an i.i.d. sample $(X_i, Y_i)$, $i = 1, \ldots, n$ from the regression model $Y = g(<b, X>) + \xi$.
- Goal: Update the estimation of the direction $b$ at each arrival of a new block of observations.

2.2 Method

- Compute the individual directions $\hat{b}_t$ on each block $t = 1, \ldots, T$ using SIR.
• Compute a common direction as

\[ \hat{b} = \arg \max_{||\hat{b}||=1} \sum_{t=1}^{T} \cos^2(\hat{b}_t, b) \cos^2(\hat{b}_t, \hat{b}_T). \]

Idea: If \( \hat{b}_t \) is close to \( \hat{b}_T \) then \( \hat{b} \) should be close to \( \hat{b}_t \).

Explicit solution: \( \hat{b} \) is the eigenvector associated to the largest eigenvalue of

\[ M_T = \sum_{t=1}^{T} \hat{b}_t \hat{b}_t^* \cos^2(\hat{b}_t, \hat{b}_T). \]

2.3 Advantages of SIRdatastream

• Computational complexity \( O(Tnp^2) \) v.s. \( O(T^2np^2) \) for the brute-force method which would consist in applying regularized SIR on the union of the \( t \) first blocks for \( t = 1, \ldots, T \).

• Data storage \( O(np) \) v.s. \( O(Tnp) \) for the brute-force method.

(under the assumption \( n >> \max(T, p) \)).

• Interpretation of the weights \( \cos^2(\hat{b}_t, \hat{b}_T) \).

2.4 Illustration on simulations

2.4.1 Scenario 1: A common direction in all the 60 blocks.

Left: \( \cos^2(\hat{b}, b) \) for SIRdatastream, SIR brute-force and SIR estimators at each time \( t \). Right: \( \cos^2(\hat{b}_t, \hat{b}_T) \). The lighter (yellow) is the color, the larger is the weight. Red color stands for very small squared cosines.
2.4.2 Scenario 2: The 10th block is different from the other ones.

Left: $\cos^2(\hat{b}, b)$ for SIRdatastream, SIR brute-force and SIR estimators at each time $t$. Right: $\cos^2(\hat{b}_t, \hat{b}_T)$. The lighter (yellow) is the color, the larger is the weight. Red color stands for very small squared cosines.

2.4.3 Scenario 3: A drift occurs from the 10th block ($b$ to $\hat{b}$)

Left: $\cos^2(\hat{b}, b)$ for SIRdatastream, SIR brute-force and SIR estimators at each time $t$. Right: $\cos^2(\hat{b}_t, \hat{b}_T)$. The lighter (yellow) is the color, the larger is the weight. Red color stands for very small squared cosines.
2.4.4 Scenario 4: From the 10th block to the last one, there is no common direction.

Left: $\cos^2(b, \tilde{b})$ for SIR datastream and SIR brute-force. Right: $\cos^2(\hat{b}, \tilde{b})$

3 Application to real data

3.1 Estimation of Mars surface physical properties from hyperspectral images

Context:

- Observation of the south pole of Mars at the end of summer, collected during orbit 61 by the French imaging spectrometer OMEGA on board Mars Express Mission.
- 3D image: On each pixel, a spectra containing $p = 184$ wavelengths is recorded.
• This portion of Mars mainly contains water ice, CO₂ and dust.

**Goal:** For each spectra \( X \in \mathbb{R}^p \), estimate the corresponding physical parameter \( Y \in \mathbb{R} \) (grain size of CO₂).

### 3.2 An inverse problem

**Forward problem.**

- Physical modeling of individual spectra with a surface reflectance model.
- Starting from a physical parameter \( Y \), simulate \( X = F(Y) \).
- Generation of \( n = 12,000 \) synthetic spectra with the corresponding parameters.

\[ \Rightarrow \text{Learning database.} \]

**Inverse problem.**

- Estimate the functional relationship \( Y = G(X) \).
- Dimension reduction assumption \( G(X) = g(\langle b, X \rangle) \).
- \( b \) is estimated by SIR, \( g \) is estimated by a nonparametric one-dimensional regression.

### 3.3 Estimated function \( g \)

Estimated function \( g \) between the projected spectra \( \langle \hat{b}, X \rangle \) on the first axis of SIR and \( Y \), the grain size of CO₂.
3.4 Estimated CO$_2$ maps

Grain size of CO$_2$ estimated with SIR on a hyperspectral image of Mars.

References


