Interactive Visual Analysis of Complex Data: Introduction, Families of Curves

Krešimir Matković
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Overview

Coordinated Multiple Views

Complex data: families of curves

- Traffic Surveillance
- Engineering
- Bio-Synaps and ICU Data
  - Heart reinervation
  - IVA of ICU Data
- Animal Paths
- Image Collection
Multidimensional Multivariate Data

Conventional approach deals with n-dim. Euclidian spaces

Each item is a point in n-dim. Space (n-tuple)

\[ Pi = [x_1, \ldots, x_i, \ldots, x_n] \]

<table>
<thead>
<tr>
<th>STATION</th>
<th>AVERAGE TEMP</th>
<th>PRESSURE</th>
<th>ELEVATION</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>1015</td>
<td>200</td>
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</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1020</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>
Coordinated multiple views

Show various dimensions simultaneously

Use mostly simple 2D views

Interaction:

- Linking & brushing
- Select items in one view and they will be highlighted in all views
Complex Data

Engineering data does not always fit to this data model

Typical simulation:
- N control parameters
- n simulation runs (n <= 2^N)
- M output values which can be mappings (f(x), x is time, crankangle,...)

Point $P_i$ is the same, but $x_i$ can be a mapping

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Complex Data

Control parameters: scalar values

\[ x_1, x_2, \ldots, x_m \]

SIMULATION

Computed responses: scalar values, curves, and surfaces

\[ y_1, y_2, \ldots, y_k, \ldots, y_n \]

FEATURE EXTRACTION

Features extracted from complex responses: scalar values

\[ z_1, \ldots, z_p \]
Mapping as a dimension 1

Such data model is common

Simulations, Meteorology, Traffic, Telecommunication, Financial data, ...

Such mappings themselves are common

Often described as 2D Euclidian space

Our approach differs from conventional

- Mapping is a dimension of the space
Mapping as a dimension 2

| STATION | AVERAGE TEMP | PRESSURE | ELEVATION | ...
<table>
<thead>
<tr>
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</thead>
<tbody>
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<td>200</td>
<td>...</td>
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<td>2</td>
<td>20</td>
<td>1020</td>
<td>300</td>
<td>...</td>
</tr>
</tbody>
</table>

| STATION | TEMPERATURE over the year | PRESSURE | ELEVATION | ...
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>(Jan,5);(Feb,8);...</td>
<td>1015</td>
<td>200</td>
<td>...</td>
</tr>
<tr>
<td>2</td>
<td>(Jan,6);(Feb,10);...</td>
<td>1020</td>
<td>300</td>
<td>...</td>
</tr>
</tbody>
</table>
Curve View

If there are N points $P_i$

And dimension $k$ is a mapping

Each $x_k$ is a function graph

There are N function graphs for dimension $k$
  – A Family of Function Graphs

Curve View displays such a family

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Interaction

Curve view in a multiple linked view setup

Need for efficient brush

Line brush
- Selects all curves which cross the line
- Very intuitive
- Easy to define
- Would be much more complex using SQL
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- Image Collections
Typical Visualization Tasks

- Exploration
- Find the unknown, unexpected
- Hypothesis generation
- Analysis
- Confirm or reject hypotheses
- Information drill-down
- Presentation

Traffic Sensor Network
(Minneapolis, St. Pauls)

- 12 weeks (84 days)
- 564 sensors
- Daily data, aggregated from measurements all 30 secs.
- \(2 \times 47376 = 94752\) graphs
  (144 \(f(t)\)-values each, one per 10 mins.)
Typical Visualization Tasks

- Visualization can be good for:
  - Exploration
  - Hypothesis generation
  - Analysis
  - Confirm or reject hypotheses
  - Information drill-down

- Presentation
  - Communicate/disseminate results

... 2 sensors, 2 days (Sun+Mon)!

[TVCG 2006]
Typical Visualization Tasks

- Exploration
  - find the unknown, unexpected
- Hypothesis generation
- Analysis
  - confirm or reject hypotheses
- Information drill-down
- Presentation

... 293 outliers (out of 47376 ≈ 0.6%)!

... negative(!) volume-values brushed...

([TVCG 2006])
Typical Visualization Tasks

- Visualization is good for:
  - Exploration
  - Hypothesis generation
  - Analysis
  - Confirm or reject hypotheses
  - Information drill-down

- Presentation
  - Communicate/disseminate results

[TVCG 2006]
Typical Visualization Tasks

- Visualization is good for:
  - Exploration
  - Hypothesis generation
  - Analysis
  - Confirm or reject hypotheses
  - Information drill-down
  - Presentation

... again the same sensor!

... just 1 outlier!

[TVCG 2006]
Typical Visualization Tasks

- Visualization is (can be)
  - exploration
  - find the unknown, unexpected
  - hypothesis generation
  - analysis
  - confirm or reject hypotheses
  - information drill-down
  - presentation

whole day no cars?!

why (just) here???

[TVCG 2006]
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Automotive Simulation

Simulation is increasingly employed

- fluid/gas flow (engine, interior, exterior, etc.)
- crash simulation, etc.

Methods

- computational fluid dynamics (CFD)
- finite element methods (FEM)
- discrete simulation

Issues

- simulation often costly (€, time)
- datasets often large, multi-dim./-variate, etc.
Questions, Goals

More information from data
- cues for future improvements
- improving expertise

Optimization
- seeing the unexpected, reading between lines
- utilizing expertise

Analyzing failures
- answering „why“-/„how“-questions
- simulation debugging
- failure analysis

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Special Challenges

Multi-variate data (many data columns)
- CFD simulation delivers dozens of attribute dims.
- Process simulation can deliver even more

Large datasets (many data rows)
- Simulation datasets: Gigabytes, ...

Spatiotemporal relations
- 3D space/object referenced
- time-referenced

Complex/nontrivial physical phenomena
Injection Design

Context:
- common rail Diesel technology
- optimization of Diesel injection

Simulation:
- simplified 1D simulation
- variational analysis wrt. boundary conditions (~$10^4$ sim. runs)
Simulation and Visualization 1

Common practice:
- define a model
- run simulation
- visualize results
- change the model
- run simulation ...
Simulation and Visualization 2

Multiple runs:
- define a model
- define control parameters
- run simulation
  - for each combination of control parameters
  - for some of the combinations (steering)
- use interactive visual analysis
  - to understand (optimize) the model
  - to understand the phenomena
Common Rail Injection

Valve body goes up
P drops

Our example

Fast simulation

Main principle

Solenoid valve controls opening and closing (injection)

High P moves needle up

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Common Rail Diesel Injection 1st case

- Control Parameters:
  - R1 = inlet / outlet
  - R2 = piston / needle
  - R3 = inlet / piston
  - $P_{rail}$ = common rail pressure
  - $SV_{open}$, $SV_{close}$ = valve open./clos. vels.
Injection Simulation

Simulation with AVL HydSim

Variations:
- 9* R1
- 9* R2
- 5* R3
- 3* P_{rail}
- 4* SV_{open}
- 4* SV_{close}

- 19440 sim. runs, multi-variate res.

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Simulation Results

Computed values:
- $m_{\text{inj}} = \text{inj. fuel mass}$
- $X_{\text{max}} = \text{max. needle lift}$
- $T_{\text{open}}, V_{\text{open}}, T_{\text{close}}, V_{\text{close}} = \text{shape params.}$

Goals:
- enough fuel (not too much)
- early inj. (not too slow)
- etc.

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Analysis: Black Box Reconstruction
Families of curves – complex data

One record = one run

Various attributes

- scalar - control parameters and scalar aggregates of state parameters
- time series – state variables

Considering function graphs as resulting values

<table>
<thead>
<tr>
<th>Run</th>
<th>Flow resistance</th>
<th>Closing start</th>
<th>Pressure(t)</th>
<th>Velocity(t)</th>
<th>…</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td></td>
<td></td>
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<tr>
<td>3</td>
<td>1</td>
<td>30</td>
<td></td>
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<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td></td>
</tr>
</tbody>
</table>
Next Step: Injection Graph Analysis

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Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Parameter Influence (box)
Analysis: Shape „boot“
Analysis: Shape „boot“
Analysis: Shape „boot“
Analysis: Shape „boot“
Electronic Unit Injector - EUI 1

One injector per cylinder

Used in Diesel engines:
- patent from 1911
- used since 1930s in trucks, locomotives, and ships
- EUI in 1990s
- mostly used in heavy vehicles

Injector design is very important
- emission reduction
- engine efficiency
Model (of an EUI Injector)

Model definition:
- standard building blocks are used
- each block has control parameters
- decide which will be varied
- state variables are computed for each block
- scalar and time series values

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Model (of an EUI Injector)

Needle Control Valve

Control parameters
- Closing start
- Opening start
- Flow resistance
- Time for opening
- Time for closing

Output:
- Volume-rate

This element serves to define a throttle controlled by timing of flow areas (switch valve). Flow area can be a function of time or crank angle.
Multiple simulation runs

AVL HydSim tool used

1D CFD – fast simulation
  ■ 10 simulation runs per minutes

7 parameters varied – 2880 runs

9 state variables considered in analysis (+ aggregates)

<table>
<thead>
<tr>
<th>Block</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>flow resistance</td>
<td>1.0; 2.0; 3.0; 4.0</td>
</tr>
<tr>
<td>I</td>
<td>flow resistance</td>
<td>1.0; 2.0; 3.0; 4.0</td>
</tr>
<tr>
<td>E</td>
<td>flow resistance</td>
<td>1.0; 2.0; 3.0</td>
</tr>
<tr>
<td>B</td>
<td>flow resistance</td>
<td>1.0; 2.0; 3.0</td>
</tr>
<tr>
<td>G</td>
<td>closing starts</td>
<td>20; 25; 30; 35; 40</td>
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<tr>
<td>G</td>
<td>opening starts</td>
<td>-15; -20; -25</td>
</tr>
<tr>
<td>H</td>
<td>opening starts</td>
<td>-15; -20</td>
</tr>
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</table>

<table>
<thead>
<tr>
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<td>pressure</td>
<td>bar</td>
</tr>
<tr>
<td>A</td>
<td>volume rate</td>
<td>mm³/deg</td>
</tr>
<tr>
<td>G</td>
<td>volume rate</td>
<td>mm³/deg</td>
</tr>
<tr>
<td>C</td>
<td>lift</td>
<td>mm</td>
</tr>
<tr>
<td>C</td>
<td>velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>D</td>
<td>volume rate</td>
<td>mm³/deg</td>
</tr>
<tr>
<td>D</td>
<td>injected volume</td>
<td>mm³</td>
</tr>
<tr>
<td>D</td>
<td>pressure</td>
<td>bar</td>
</tr>
<tr>
<td>F</td>
<td>pressure</td>
<td>bar</td>
</tr>
</tbody>
</table>
Interactive Visual Analysis

Results are available:

- use interactive visual analysis
  - to understand (optimize) the model
  - to understand the phenomena
- CMV system used
- many parameters – many views
- engineer has to know what is depicted in each view
The Model View

Engineers are familiar with model view

We want to show results and control parameters in blocks

Control and state variables

Multiple runs!
- various values for control parameters
- various values for state variables - time series

Limited space – three levels

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Three Levels

Show control parameters on left, state variables on right

Up to 3 variables (user selects them)

Level one
- histograms used
- if state variables are time series – use aggregates

Level two
- double width and height
- up to six histograms, or fewer larger
- scatter plot also possible (not used in our case)
- aggregates of state variables still used

Level three
- block can not be larger
- floating view with map and time series data

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Analysis

Data derivation and aggregation integrated in the system

Successfully used to analyze and tune EUI for different operation modes

Complex Interaction – Simple Data

vs.

Simple Interaction – Complex data
Analysis – the High Power Mode 1

Square shaped injection curve

High injection pressure
- we want a lot of fuel

Blocks C and D are of main interest

3rd level view configured using model view

3 families of curves

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Analysis – the High Power Mode 2

Select curves with steep rise
- line brush with limited crossing

Refine selection
- only high pressure at the injection start
- stronger fuel penetration – higher power

Refine once more
- subtract too slow rising
- or change limit of the crossing

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Analysis – the High Power Mode 3

Second needle opening
- undesired behavior
- can be seen in the curve view
- maybe additional curves are hidden

Use a derived family of function:
- first derivative
- more curves detected
- explore why (see paper)

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Analysis – the High Power Mode 4

Select curves with step rise
- line brush with limited crossing

Refine selection
- only high pressure at the injection start
- Stronger fuel penetration – higher power

Refine once more
- subtract too slow rising
- or change limit of the crossing

Exclude second needle opening

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Analysis – the High Power Mode 5

0.063
D: volume Rate INT 0.022

9.74
11.11
A: volume rate MEAN

All parameters are always highlighted in the model view

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Unlimited Possibilities

Low Consumption mode

Instead of brushing curve view

Use histograms of min and max aggregates of 1st derivative
Integration of Model view into CMV

Helps users in:
- figuring out the basic behavior based on aggregates
- identifying important elements for a given scenario
- configuring views, select what is displayed by one click
- connecting views to originating models

Very positive feedback from domain experts
- will be included in commercial software in near future
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- Image Collection
Heart Reinervation 1

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Heart Reinervation 2
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ICU Data

Modern Intensive Care Unit

- a lot of high technology equipment
- routinely logging of
  - many physiological measurements
  - laboratory results
  - interventions information
- these information can help intensive care physicians to

understand physiological, pathological and therapeutic processes
and so, consequently, to improve medical care
Usage of Data

Huge amounts of data available

Great potential but:
- many proprietary formats, data bases rarely merged
- statistical models are complex and hard to develop without merged DBs
- communication between medical and statistics experts

State of the art
- various regression models and advanced statistics
- Protocols (researchers – daily practice)
- APACHII Score, for example

Interactive Visual Analysis
- novel concept for ICU medical researchers
Data 1

~1500 patients

<table>
<thead>
<tr>
<th>Time</th>
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<th>Age</th>
<th>apa</th>
<th>gsc</th>
<th>temp</th>
<th>lnr</th>
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<td>23</td>
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<td>37,6</td>
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<tr>
<td>01:00</td>
<td>1404</td>
<td>43</td>
<td>18</td>
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<td>40,4</td>
<td>1</td>
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<td>01:00</td>
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<td>24</td>
<td>12</td>
<td>38,2</td>
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<td>4965</td>
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<td>7</td>
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Huge database
- complex processing and analysis

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Family of Curves

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</table>

...
Workflow

Prepare the data according to the new data model

Derive data if necessary

Domain Experts have to familiarize with the tool

Add specific features needed by domain experts depending on their tasks

More complex data exploration and analysis
Prepare the data according to the new data model. Improvements of curve view were necessary for different lengths of curves.

- Support for gaps for small and large gaps
- Depict start–end point
- Fill the missing part (optionally)
- Mouse–over highlighting

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Additional Features

Introduction of box-plot into CMV

- Experts were used in an interactive setup
- Very powerful overview method
- Support for multiple brushes
  - Inverse brush – show brushed records, non- brushed records, and all
  - If last brushed dimension is boolean, useful
- Brush summary view
  - Useful if last brushed dimension is boolean

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Case Study 1 – Confirming a Hypothesis

We are exploring sodium concentration

Hyponatraemia – sodium too low, < 130 mmol/L

Hypernatremia – sodium too high, > 150 mmol/L

Sodium concentration available as a curve per patient

Known hypothesis – patients with hypo- or hypernatremia have a higher mortality rate

Brushing hypernatremia patients

- Use curve view and a long horizontal brush
- Compute maximum aggregate – curve -> scalar and use conventional views

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Case Study 2 – Exploring Variability

We suspect that not only absolute values, but rate of change has influence on mortality.

First derivation aggregate curve - curve

Using standard techniques to explore the change.

Hypernatremia with rapid fall very dangerous. Special care has to be taken when reducing sodium level.

We also explored patients with rapid fall or rise but no hyper or hyponatremia.

 unexpected finding! 

High sodium level variability increases mortality!
Case Study 3 – Interactive drill down

New data model makes advanced drill down possible

The timing of fall/rise can be easily specified
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The Domain - Ethology

Scientific study of animal behavior
- neural mechanisms of learning processes
- physiological processes
- influence of drugs
- ...

Types of ethological studies
- open field (OF)
- open field with object placement task (OPT)
- mazes
- ...

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The Study - Object Placement Task

Observation I
- open field (120cm x 120cm) with two identical objects
- observation time: 5 minutes

Observation II
- one object of observation I setup is displaced
- observation time: 5 minutes

Evaluation
- spatial reference memory
- locomotor activity, anxiety related behavior
Data Acquisition

Video Tracking System
- records path of animal
- parameters:
  - total distance
  - average speed
  - time spent in area X
  - field crossings
  - turn arounds
  - ...

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Entry: Interactive Visual Analysis

Conventional approach
- statistical evaluation
- a single path can be examined at a time

New approach
- compare tracks of all animals (whole ensemble) interactively
  => integrate the path itself in the analysis
- coordinated multiple views (CMV)
Coordinated Multiple Views

- scatter-plot, histogram, parallel coordinates, ...
- curve view
- line brush
- linking and brushing
- composite brushing
- focus + context

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Coordinated Multiple Views

- scatter-plot, histogram, parallel coordinates, ...
- curve view
- line brush
- linking and brushing
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Data Model

Multivariate, multidimensional data

- a record contains
  - animal parameters: ID, age, ...
  - aggregated path parameters: total path length, average speed, time spent in a specific area, ...
  - time series parameters (Konyha et. al): path, distance traveled
- number of records: 814
Interactive Analysis
Validating evaluation parameters

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Interactive Analysis
Identifying Patterns in Paths

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T-Maze 1

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T-Maze 2

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Thank you!

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Krešimir Matković

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