Data Fusion in Wireless Automation

Mikael Björkbom
Lecture Content

- Introduction
- Data fusion categorizations
- Consequences of going wireless
- Data fusion methods
- Conclusion
Part I

INTRODUCTION
Data Fusion

- A multitude of applications:
  - Military: surveillance, defense, intelligence
  - Civil: maintenance, localization, reconnaissance
  - Medical diagnosis
  - Weather monitoring
Introduction: Motivation

- WSNs are intended to use hundreds to thousands of sensor nodes to monitor and measure phenomena in a large area over a long period of time.
- The consequent huge amount of data must be efficiently processed to extract useful information.
- Measurements may have large uncertainties.
- Therefore: data have to be processed.
Introduction: Motivation

• Sources of uncertainty in the data:
  ♦ Poor calibration
  ♦ Malfunctions
  ♦ Accuracy of sensor
  ♦ Time-synchronization of sensors
  ♦ Poor knowledge of the sensor/environment/phenomena relationship
  ♦ Poor knowledge of the monitored phenomena

• Therefore: data have to be processed
Introduction: A Definition

A definition for data fusion (L. Wald, Armines / Ecole des Mines de Paris):

Data fusion is a formal framework in which are expressed the means and tools for the alliance of data originating from different sources. It aims at obtaining information of greater quality; the exact definition of 'greater quality' will depend upon the application.
Sensor Networks & Wireless Automation

- Data fusion used mostly in sensor networks
  - Many sensors
  - Collaborate, refine data
- Can also be applied in wireless automation
  - Estimation of non-measurable quantities
  - Estimation of missing information (packet drops)
  - Decision making
Outline of Data Fusion in Automation

• Operation of data fusion in automation:

  Sensing
  ↓
  Signal processing
  ↓
  Feature extraction
  ↓
  Decision making  Feedback control

• Notes:
  * signal processing is essentially pre-processing
  * feature extraction is “where the data fusion magic happens”
Part II

DATA FUSION CATEGORIZED
Data Processing Hierarchy

• Architecture of data processing in wireless automation can be (for example):
  ♦ Centralized
    • a central sink node processes sensor node data
  ♦ Decentralized
    • processing is performed locally at each node using also the communication from other nodes
  ♦ Tree
    • hierarchical levels down from the sink node
  ♦ Clustered
    • nodes divided to hierarchical levels – processing in higher level nodes (sink nodes, cluster heads)
Data Processed

- Data Fusion is the process of combining data and knowledge from different sources to maximize the useful information content.
- The fusion level defines the level at which the information is fused:
  - Data-level: combination of (unprocessed) sensor data
    - in automation: improving noisy measurements
  - Feature-level: combination of features extracted from data
    - in automation: extraction of the feedback and monitoring variables
  - Decision-level: combination of decisions based on local data
    - in automation: automated decision-making
Data Processing Types

• Data processing in wireless sensor networks can be divided into:
  - Data compression: eliminating the redundancy from the data
  - Data aggregation: collecting and combining data coming from a single sensor type
  - Data fusion: combining data measured by several types of sensors and other information sources that are possibly available

• Types are very close to each other and the division between them is not clear – it is easier to talk about data fusion
Data Compression/Aggregation

• Data compression
  ◦ Fit the same information in a smaller space
  ◦ Based on the correlation existing in the data

• Data aggregation
  ◦ Uses data compression to compute an aggregated value ("weighted sum") from data coming from the children nodes
  ◦ Overall energy saving by minimizing the number of transmissions to the sink node

• Correlation of measurements can be due to
  ◦ locations of the sensors
  ◦ nature of the measured phenomena
  ◦ nature of the measurement
Advantages

• Important aspects of data aggregation:
  ♦ Energy/Communication efficiency
  ♦ Resistance against attacks

• Data fusion advantages:
  ♦ Robustness and reliability
  ♦ Better quality of the deduced information
  ♦ Better discrimination between available hypotheses
  ♦ Control over the explosion of the available amount of data
The Role of the Informational Content

• Need for some criteria to grade the informational content of a packet
• Different link-local error control mechanisms depending on the informational content of a report

Each packet contains:
  - Value
  - Number of sensors that contribute to the value
  - Covered area

Light disturbance if message is lost

Heavy disturbance if message is lost
More Characteristics

- Reporting of sensor nodes can occur based on different options
  - Periodical reporting
    - e.g. measurement for feedback control
  - Answering requests of the sink node
    - e.g. monitoring of node measurements
  - Event triggered reports
    - e.g. alarms for event monitoring
- Measurement node movement
  - Mobility changes measurement correlation between nodes
  ➔ More options for data fusion type
Part III

CONSEQUENCES OF GOING WIRELESS
Issues to Consider in Data Fusion of Wireless Automation

- Wireless data fusion raises a few important topics to be considered:
  - Missing and delayed measurements
  - Performance restrictions
    - Limited communication bandwidth
    - Computational power, Memory, Battery power
    - Especially in large scale systems
  - Data fusion architecture

- The choice of architecture depends on
  - the data used
  - the need of robustness against hostile attacks
  - communicational and computational restrictions
Missing and Delayed Measurements

• Due to the wireless communication and/or measuring imperfections, the measurements can be
  - Delayed
  - Out-of-order
  - Missing
  - Asynchronous

• Data alignment
  - Transforming data from different coordinates/time to same frame-of-reference for further processing

• Data fusion has to know how to cope with these situations
Data Fusion Architecture

• Centralized architecture:
  ✷ simple communication – all measurements are communicated into one node
  ✷ all depends on one fusion centre – robustness against malfunctions questionable

• Decentralized architecture:
  ✷ all nodes communicate with all other nodes – heavy communicational burden
  ✷ not dependent on single node – robust against malfunctions

• Cluster and tree architectures are "in between" of these two
An Architecture Example

• Consider a simple example system with six nodes (circle = measuring node, red = data fusion node)

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Fusion centres</th>
<th>Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized</td>
<td>1</td>
<td>5 (one-way)</td>
</tr>
<tr>
<td>Decentralized</td>
<td>6</td>
<td>6 \cdot 5 = 30 (two-way)</td>
</tr>
<tr>
<td>Clusterized</td>
<td>2</td>
<td>4 + 2 = 6 (one-way communication to fusion centres, two-way between them)</td>
</tr>
</tbody>
</table>

• Choice of architecture has a trade-off
  - More data fusion nodes → more robustness, but more communication and sophisticated nodes required
A Method Example

- Fusion node performance restricts also the fusion methods
- Example: when combining two measurements of a dynamic system, should I use

  a) Measurement average

  \[ \bar{y} = \left( y_1 + y_2 \right) / 2 \]

  b) Kalman filter

  \[ \hat{x}_{kk-1} = F \hat{x}_{k-1|k-1} + Bu_{k-1} \]
  \[ P_{kk-1} = FP_{k-1|k-1} F^T + Q \]
  \[ S_k = HP_{kk-1} H^T + R \]
  \[ K_k = P_{kk-1} H^T S_k^{-1} \]
  \[ \hat{x}_{kk} = \hat{x}_{kk-1} + K_k \left( y_k - H \hat{x}_{kk-1} \right) \]
  \[ P_{kk} = (I - K_k H) P_{kk-1} \]

- Optimality comes with high price...
Part IV

DATA FUSION METHODS
Data Fusion: a Biological System

Memory
Experience
A priori knowledge
Deductions
Model of the environment
Actions
- Level 1: data alignment, association, tracking, identification
- Level 2: groups entities together
- Level 3: defines the threats the enemies pose
- Level 4: optimizes the fusion process
Data Fusion Operations

PRE-PROCESSING
- Linear and non-linear PCA
- FFT
- Cepstrum
- Enveloping
- Thresholding
- Wavelets

DATA ALIGNMENT
- Distance metrics: Euclidean, Minkowsky, Manhattan, Mahalanobis
- Correlation metrics
- Least square, Mean square error, Maximum likelihood
- Kalman filtering
- Neural networks

POST-PROCESSING
- Inference: Maximum a posteriori, Neyman-Pearson, Bayes,...
- Voting, Consensus, Scoring
- Fuzzy logic, Genetic algorithms

TKK | Control Engineering
AS-74.3199 Wireless Automation  28
Methods for Data Fusion

• **Statistical fusion techniques:**
  - Mean, variance...
  - Kalman Filtering (KF)
  - Principal Component Analysis (PCA)
  - Bayesian methods

• **Non-statistical fusion techniques:**
  - Fuzzy-logic
  - Rule-based fusion
  - Voting techniques
Keeping It Simple and Stupid

• Using simple statistics can be often enough for data fusion
  ♦ mean → simple use of multiple measurements
  ♦ variance → information of accuracy, reliability
  ♦ mode, median → voting in decision fusion

• Decision fusion can be done with user-defined heuristic rules
  ♦ Rule bases (if ... then)
  ♦ Fuzzy logic

• However, simple approaches are necessarily not enough, e.g., in dynamic systems
KISS Example

- Consider a five sensor system measuring sine-wave with gaussian noise

- Original signal
- Noisy measurements
- Data fusion by average

→ Accurate, simple fusion
KISS Example

- Same example, this time one sensor has a period with a larger noise

- Original signal
- Noisy measurements
- Data fusion by average
- Standard deviation of measurements

→ Simple fusion with quality indicator
Kalman Filter

- KF is optimal linear filter for dynamic systems with Gaussian noise.
- KF is based on state-space model:
  \[ x(k+1) = F(k)x(k) + G(k)w(k) \]
  \[ z(k) = H(k)x(k) + v(k) \]
  
  \( z \) is the measurement, \( x \) is the state to be estimated.
  \( \rightarrow \) state estimation and measurement filtering possible.

- Noise covariance matrices:
  - Process noise: \( \text{cov}(w(k)) = Q(k) \)
  - Observation noise: \( \text{cov}(v(k)) = R(k) \)
Decentralized Kalman Filter

• KF can be put into form of decentralized Kalman filter (DKF), which is mathematically equivalent to centralized filter
  ➢ Possible for genuine decentralized data fusion
• Starting point is the dynamical model and partitioned observation equation

\[
\begin{align*}
x_i(k+1) &= F_i(k)x_i(k) + G_i(k)w_i(k) \\
z_i(k) &= H_i(k)x_i(k) + v_i(k)
\end{align*}
\]

\[
\begin{align*}
z(k) &= \begin{bmatrix} z_1^T(k), \ldots, z_m^T(k) \end{bmatrix}^T \\
H(k) &= \begin{bmatrix} H_1^T(k), \ldots, H_m^T(k) \end{bmatrix}^T \\
v(k) &= \begin{bmatrix} v_1^T(k), \ldots, v_m^T(k) \end{bmatrix}^T
\end{align*}
\]

• That is: \( m \) observing nodes with data fusion
DKF Algorithm

- DKF is based on so-called information filter form of KF, where
  \[ \hat{y}_i(k|l) \triangleq P_i^{-1}(k|l)\hat{x}_i(k|l) \quad Y_i(k|l) \triangleq P_i^{-1}(k|l) \]
- DKF has five stages: prediction, local update, communication, global update and estimation
- DKF prediction equations for node \( i \):
  \[
  Y_i(k + 1|k) = \left( F_i(k + 1)Y_i^{-1}(k|k)F_i^T(k + 1) + G_i(k + 1)Q_i(k + 1)G_i^T(k + 1) \right)^{-1}
  \]
  \[
  \hat{y}_i(k + 1|k) = Y_i(k + 1|k)F_i(k)Y_i^{-1}(k|k)\hat{y}_i(k|k)
  \]
- DKF local update for node \( i \):
  \[
  i_i(k + 1) = H_i^T(k + 1)R_i^{-1}(k + 1)z_i(k + 1)
  \]
  \[
  \tilde{y}_i(k + 1|k + 1) = \hat{y}_i(k + 1|k) + i_i(k + 1)
  \]
  \[
  I_i(k + 1) = H_i^T(k + 1)R_i^{-1}(k + 1)H_i(k + 1)
  \]
  \[
  \tilde{Y}_i(k + 1|k + 1) = Y_i(k + 1|k) + I_i(k + 1)
  \]
DKF Algorithm

- Communication to other nodes:
  - state error information \( \mathbf{i}_i \)
  - variance error information \( \mathbf{I}_i \)
- Global update

\[
\hat{y}_i(k+1|k+1) = \hat{y}_i(k+1|k) + \sum_{j=1}^{m} \mathbf{i}_j(k)
\]

\[
\mathbf{Y}_i(k+1|k+1) = \mathbf{Y}_i(k+1|k) + \sum_{j=1}^{m} \mathbf{I}_j(k)
\]
- State estimate

\[
\hat{x}_i(k+1|k+1) = \mathbf{Y}_i^{-1}(k+1|k+1)\hat{y}_i(k+1|k+1)
\]
DKF Algorithm

• Information flow in the node $i$:

  $$\hat{y}_i(k|k-1) \rightarrow \text{Prediction} \rightarrow \hat{y}_i(k|k-1) \rightarrow \text{Local update} \rightarrow i_i(k)$$

  $$\hat{y}_i(k|k-1) \rightarrow z^{-1} \rightarrow \hat{y}_i(k|k) \rightarrow \text{Global update} \rightarrow i_j(k), j \neq i$$

• Requires very much communication
  - Communication breakdown does not disable filter, but the result is not optimal anymore
Short Summary on DKF from the Wireless Point-of-View

• Using DKF in large scale systems fully centralized is not recommended in wireless systems

• Using DKF in clusters possible in large scale systems/
  Run consensus algorithm to update global estimate
  - Reduces communication requirements significantly
  - But every node has own version of the global estimate
Placement of Estimator

- Estimate and transmit estimate
  - Optimal estimate
  - What if estimate not received?

- Receive measurement and estimate
  - Always local estimate
  - Not optimal
Part V

CONCLUSIONS
If You Ever Have to Build One

- Topics to keep in mind while planning data fusion for wireless automation
  - **Accuracy**: How accurate the data fusion products have to be?
  - **Reliability**: How important is robustness against malfunctions?
  - **Computational complexity**: Do nodes support computationally heavy methods?
  - **Communication burden**: How much communication can wireless links handle?
  - **Cost**: How much you have dough?
    - A real-life multi-objective optimization problem…
If You Ever Have to Build One

• Answers can be found in design phase by choosing
  - Architecture: clusterization or decentralization
  - Methods: data fusion method to use
  - Node hardware: enough resources for data fusion

• The essential issue: know your system