Multi-sensor data fusion and sensor fusion models

Jozef Jurčo, Jozef Puttera, Roman Berešík
The Armed Forces Academy of General Milan Rastislav Štefánik,
Demänová 393, 031 06, Liptovský Mikuláš
jurci0@yahoo.com, jozef.puttera@aos.sk, roman.beresik@aos.sk

Abstract: Currently, the data fusion from different sources, whether they are sensor networks including classic digital or analog sensors, or sensors representing human resources, becomes a key element in evaluation of the measurement results, simplification decision-making processes and corrections of errors. In respect of the wide range of fusion methods usage in variety of scientific disciplines and areas such as robotics, medicine, military and economy, there is strong motivation for design, development and evolving of the various fusion models. The areas of applications are not only limited to previously mentioned applications, but they are also applicable in other scientific disciplines. The sensor fusion techniques offer the tools for sensor data processing in order to enhance the system capability and reliability. The goal of this article is to analyze the basic fusion models and architectures currently used for multi-sensor fusion.

Keywords: Data fusion, Multi-sensor data fusion, Sensor networks

1 Introduction

The aim of the multi-sensor data fusion is to combine information from multiple sources (sensors, human resources, internet etc.) in order to achieve the event description which can be hardly obtained from one independent sensor or source, eventually from object as whole [1]. Typical applications, where the multi-sensor fusion methods and models can be used, include localization of objects [2], robust navigation solution (satellite positioning systems, inertial measurements, and odometry), sensor networks for surveillance or applications aimed at assessing the state of the environment [3]. The sensor networks used in surveillance applications for detection, localization and identification of the objects (persons, vehicles, objects, gas clouds etc.), can created by spatially distributed acoustic, seismic, magnetic sensors, radars and sensors. The basic common feature of these applications is a collection of data or information from different sources. Together, these data provide basis for more accurate description of the situation, but at the same time, it brings problems with integration of individual parts of gained data. This fact causes that the systems are more complex and complicated. From this reason, over the time, several structures-models have been evolved, which separate the various relative entities, make the entire system well-arranged and allow more efficient problem solving. One of the first fusion models, where the implementation of terminology and structuring of
individual units was used is JDL (Joint Directors of Laboratories) fusion model [3]. In addition to the model, several additional models were designed such as Waterfall, Boyd, LAAS, Omnibus, Dasarathy, Thomopoulos, Durrant-White and Endsleys. The purpose of this article is to analyze typical widely used fusion models, their main features and possible use in practice.

2 Fusion architectures and models

Generally, multi-sensor data fusion architectures and models can be classified according to various criteria. One possible classification is structured along the following types of groups [1].

1. Centralized – decentralized,
2. Local - global interaction portion of the fusion of architecture,
3. Modular – monolithic,

These individual components (classes) interact with each other and thus produce different fusion models. There is several fusion models widely used in practice. Some of them are listed below:

- Centralized, global interaction, hierarchical (DFRA),
- Decentralized, global interaction, heterarchical (SEPIA, MESSIE system),
- Decentralized, local interaction, hierarchical (RCS, LSS, ILLS),
- Decentralized, local interaction, heterarchical (ASN network).

The above mentioned classification is one possible view of the sorting and classification of fusion architectures and models. The categorization of architectures and models is a complex problem and every user can thus create a myriad of criteria for evaluating these systems. Currently, various fusion models and their mutual combinations are used. Among some of the most used fusion architectures and models, we can include the following models:

- JDL data fusion model,
- Waterfall model,
- Boyd control loop (OODA loop),
- LAAS architecture,
- Omnibus data fusion model,
- Dasarathy data fusion model.

2.1 JDL data fusion model

JDL fusion model [3] was created as hierarchical model, which is currently divided into five different levels. The levels are divided as follow:
Level 0 – Source Processing/Assessment. This level is designated for estimation and prediction of signal or object conditions based on data association signals,

Level 1 – Object Assessment. The estimation and prediction of entity states is done on the basis of associations of observation-tracking, an estimation of following discrete state (e.g. data processing),

Level 2 – Assessment of the situation. The goal is to estimate and predict the conditions among the entities by comprising their structure of relations, communications (e.g. information processing),

Level 3 – Estimate of importance. The aim is to estimate and predict the effects (consequences) of planned situation, or estimate following action of participants. The next stage is interaction among the plans of actions of multiple participants (e.g. threat assessment and mission requirements),

Level 4 – Element of resource management. It involves the improvement of process. Adaptive data collection and processing of support objectives (sensor management and expansion of information systems) are implemented,

Level 5 – Element of knowledge management. This level involves the modification of cognitive processes, adaptive decision, adaptive information acquisition and display of data to support decision-making process.

Hierarchical division of JDL fusion model (fig. 1) allows further dividing of fusion levels into sublevels.

Fig. 1. JDL model [similar in 8]

The key part of the all fusion processes is data association. During the fusion process and also signal and information processing, sensors unreliability and inadequate information fusion may cause problems and subsequently the sensor fusion outcomes can be useless for decision making process in sensor applications where the sensor data fusion is applied. The JDL model data assessment (Level 0-1), situation assessment (Level 2-3), sensor management and user process improvement (Level 4-5, user refinement), if properly applied, can correct these errors fusion. While every
level needs to merge information from lower levels, improvement of information fusion is dependent only on the specific user. Other important areas in fusion models are the security control of information and event planning. There are number of solutions related to the centralized and distributed control systems. However, it is important to mention, that the information or displayed data on the interface (e.g. PC), do not reflect the information obtained from the lower levels, but represent the fusion and analysis of these data. Once the action or decision is taken, new information should be presented as operational information feedback to measures taken in previous step. One of the essential tasks implemented in the JDL model is providing the quality information assessment (information provided by the fusion of data, level 0-5). Base on this knowledge, fine-tuning of the system as a whole is then performed.

2.2 Waterfall data fusion model

Another fusion model, which the fusion community uses, is Waterfall model [8]. This model is based on hierarchical order (fig. 2). The sensor model is updated based on the feedback from the decision-making level and feedback components are used in multi-sensor system for recalibration and reconfiguration of data collection system.

Waterfall model is divided into three levels:

- **Level 1** – This level involves the transformation of raw data in order to ensure the required information about the environment,
- **Level 2** – Feature extraction and data fusion. These processes are carried out for the purpose of obtaining initial (provisional) data assessment. The objective is to minimize the data content. The output of this level is a list of estimated probabilities,
- **Level 3** – This level refers to the event object. The possible actions for particular events are arranged based on the information collected in databases and they are interpreted easily in understandable form. Subsequently, possible ways of action for certain situation are compiled.
2.3 Boyd control loop

Boyd loop is named after Col. Boyd, who defined the OODA (Observe, Orient, Decide and Act) cycle. The cycle was primarily designed to solve problems (decision) in warfare, but the principle itself is applicable in many areas. The OODA cycle must be controlled sequentially, whereby the model can be used for decomposition of compressed timeframes in logical and sequential manner. Boyle diagram (fig. 3) shows, that all decisions are based on the observation and the development of the situation with the assumed filtration of problem that can occur.

![OOODA cycle diagram](image)

Observations are represented by raw data on which decision-making and implementation is made. According to Boyd control loop, the decision occurs in repeated cycles of observation-orientation-decision-implementation steps. The main advantage of this model is its tempo. The cycle is divided into the following phases:

- **Observations phase** consists of the processes of the gathering information in regard to the interest situation,
- **Orientation phase** involves the processes which analyses the information relating to the situation of interest,
- **Decision-making phase** consists of processes describing their own course of action based on knowledge gained during the previous phase,
- **Implementation phase** consists of processes containing the current course of action.

The Boyd model represents the stages of the closed control system, but it doesn’t offer the possibility to identify and separate the different sensor fusion tasks.

2.4 Omnibus model

The omnibus fusion model is a hybrid of Boyd, Dasarathy and Waterfall models, and it consists of four main modules shown in fig. 4. These modules are designed to solve
the different fusion tasks belong to particular predispositions of the functional module. In spite of the fact that, the Omnibus is basically just extending the OODA control loop, this model offers better structuring of the processing levels in terms of level of abstraction and it has two level of abstraction.

First, the model characterizes the overall structure of model. Second, same structure can be used for modeling of the single subtasks of the particular system. However, due to the fact, that the Omnibus fusion model doesn’t support the horizontal partitioning into tasks, which is used in distributed sensing and data processing, this model also does not support the decomposition into modules. Therefore, the modules cannot be implemented separately, separately used and reused for different applications.

2.5 LAAS architecture

There are several applications where the LAAS architecture can be applied. One of application where the LAAS architecture is used is the design and implementation of the mobile robots with the respect to real-time and reuse of the code. Current robotic systems often consist of variety of the sensor and sensor systems. Therefore it is obvious that the sensor fusion models are employ in the mobile robotic systems. The LAAS architecture [6, 12] consists of three levels (basic structure is shown in fig. 5):

- **Functional level** (low-level layer) is based on the Genome means-modules. In the genome modules, there are two known communications direction. Communication direction based on reports (mailbox), or communication direction based on shared memory (posters).
- **Execution control level** (exogenous module) has two parts. The first one, safety section controls the behavior of the system and the second one, manages low-level functional layer.
- **Decision-making level** (OpenPRS, IxTeT) is responsible for the planning and management of actions. The implementations of the decision-making levels are varied. The simple actions are written in OpenPRS application, so that they react to events from the environment, while IxTeT implementation is much more complex than the OpenPRS is.

![LAAS architecture](image)

Fig. 5. LAAS architecture [8]

The advantage of this architecture is that OpenPRS, IxTeT software tools are available as freeware software and it is not required additional program coding. The same rule is applied to the source code.

### 2.6 Dasarathy model

Dasarathy [6, 7] defined category of data fusion functions based on the types of data, information that is processed and the types of information that results from the process. The Dasarathy fusion model (fig. 6) is based on fusion functions as opposed to tasks and may therefore be integrated in any fusion activity.

The model is divided into three levels:
- Data - specific sensor data,
- Features - transition level information,
- Deciding - symbols or assumptions.
Conclusion

Based on the above mentioned analysis, general fusion models principles and rules how they are used in conjunction with the sensor systems, it is hard to determine versatile fusion model for particular sensor application. The design and development of sensor systems and data gathering from multiple sensors is complex problem. For this reason, for efficient data gathering and its signal processing it is possible to use multiple fusion models, or their combinations. The typical example is OMNIBUS model, which is the combination of three fusion models-Boyd, Waterfall and Dasarathy. Another problem is the evaluation of each model. It is possible to define their own evaluation criteria, thus can be drawn different conclusions. From a practical point of view, fusion models like JDL, Waterfall are designed to deal with high-level processes, however it is not precluded their use in the processing of low-level processes. Their disadvantage is lower flexibility and processing speed comparing to "low-level" model like BOYD and OMNIBUS. The advantage of use the LAAS fusion model is the existence of software functional tools (OpenPRS, IxTeT) for rapid prototyping.

Further research will be focused on design and development of the magnetic sensor systems and conducting of data fusion from these sensors in order design accurate magnetic localization system. The next steps will be to analyze the fusion methods used in upper mentioned fusion models and also their accuracy and suitability for specific tasks in magnetic measurements will be evaluated.

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