Multi-sensor Data Fusion Architectures Revisited

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***Abstract*—Selection of the multi-sensor data fusion (MSDF) architecture is one of the key tasks in the design of a multi-sensor system. The emergence of systems with large number of sensors, e.g. Internet of things, could bring novelty into this well studied subject. In this study, we address three aspects of MSDF architectures: classification, optimal selection, and standardized presentation. We classify the known architecture types according to all the three of the criteria found in the literature, while previous works only used one or two. We suggest that the optimal selection of MSDF architecture is a multi-objective optimization problem, and qualitatively define the objective and decision spaces. Finally, we suggest that the Systems Modeling Language could be used as a standardized means for presenting MSDF architectures.**

I. Introduction

Integration of multiple sensors into a system used to assess some phenomenon implies the use of multi-sensor data fusion (MSDF) techniques. MSDF refers to combining the "data from multiple sensors, and related information from associated databases, to achieve improved accuracies and more specific inferences than could be achieved by the use of a single sensor alone" [1].

The phenomenon which is assessed could refer to various things: situation in the airspace (in air traffic control (ATC)), weather conditions (in meteorology), levels of pollution (in environmental monitoring), etc. If the phenomenon is inherently distributed, the sensors usually have to be distributed, too. It seems that, historically, MSDF was studied mostly in the context of phenomena consisting of multiple moving objects (e.g. airplanes in ATC), and so the terminology used is geared to such types of phenomena. A distributed multi-sensor system generally consists of multiple distributed sensing nodes (sensors) and one or more processing nodes (processors), all interconnected. In sensors, key quantities describing an object are extracted from raw signals, forming an abstract representation of potential object, called an *observation* (terms *measurement*, *contact*, *plot*, are also used depending on application domain, and will be regarded as synonyms in this study). In processors, observations are processed to confirm the existence of objects, and to estimate their states, classes, and identities. Abstract representation of a confirmed object is usually called a *track*.

Architecture, in general, refers to significant (or strategic) aspects of system's structure and behavior [2]. In distributed multi-sensor systems, MSDF architecture (also known as fusion/tracking/track architecture) captures strategic decisions regarding partitioning of processing tasks onto a set of distributed processors. MSDF architecture consists of three components [3]: 1) communication graph (which represents network connectivity between nodes, i.e. sensors and processors), 2) information graph (which represents detailed flow of information among interconnected nodes), and 3) information content (which defines what exactly is communicated among nodes). Communication graph describes structure, while information graph describes behavior.

Traditionally, selection of the MSDF architecture is regarded as one of the key tasks in the design of a multi-sensor system [4]. MSDF has been utilized for a long time, within systems with small number of large sensors (e.g. in ATC), and it may seem that what needs to be known about MSDF architectures has already been said. However, the emergence of systems with large number of (small) sensors, e.g. wireless sensor networks (WSN), or Internet of things (IoT), justifies a revisit to the topic of MSDF architectures, having in mind their strategic importance.

This study addresses three topics related to MSDF architectures: 1) classification of MSDF architectures, 2) optimal selection of MSDF architecture for particular system, and 3) standardized presentation of MSDF architectures.

The rest of the paper is organized as follows. Research questions are formulated in the second section. Methodology for answering the research questions is described in the third section. Our findings are presented and discussed in the fourth section, while the fifth section concludes the paper.

II. Research Questions

Before formulating the research questions, we have to introduce the terminology which will be used in the rest of the paper. There are multiple MSDF architecture *types*, which are distinguished by differences in communication graphs, information graphs or information content. Given a set of classification criteria, there are a finite number of MSDF architecture *classes*. One class can contain zero, one, or multiple types. If a class contains multiple types, it means that the types are indistinguishable by the chosen set of classification criteria. Particular multi-sensor system utilizes a particular MSDF architecture *realization*. Unlike types, realizations have the numbers of nodes (processors, sensors) specified. A realization implements a type, and can even implement multiple types, on different hierarchy levels.

We formulate three research questions, labeled Q1, Q2 and Q3.

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Q1: How can MSDF architecture types be classified?

Existing studies, such as [3], [5], [6], [7], used different (sets of) classification criteria, which probably indicates that neither of these studies has complete findings on MSDF architecture type classification. Thus, further work is needed.

Q2: How to optimally select the MSDF architecture realization for a particular system?

Existing studies, such as [3], [5], [6], [7], provided comparisons between MSDF architecture types or classes, but did not provide a generally applicable framework for selecting the MSDF architecture realization.

Q3: Can MSDF architecture realization be described using Systems Modeling Language (SysML)?

Although the free form block diagrams, used to describe MSDF architecture realizations in existing studies, are mostly intuitively clear, using a standardized visual language, such as SysML [8], could facilitate communication between the researchers and/or professionals involved in MSDF.

III. METHODOLOGY

To answer Q1, we perform literature review followed by further analysis. We review the existing studies to find the classification criteria being used so far, and attempt to create a union of the criteria from the previous studies. Then we review the existing studies for particular architecture types and classify the types using the union of the criteria.

To answer Q2, we perform literature review followed by further analysis. Based on the preliminary survey of the literature, there are multiple criteria/objectives for selection of MSDF architecture realization for a particular system. Thus, architecture realization selection is a multi-objective optimization (MOO) [9] problem. We review the existing studies to enumerate the criteria/objectives which were used so far for comparing the architectures. Then we attempt to expand the list of objectives with those not used in existing studies, but relevant for the problem, taking into account emerging types of multi-sensor systems, like IoT. We also attempt to figure out which are the decision variables for the problem.

To answer Q3, we attempt to present the communication and information graphs of an architecture realization using SysML diagrams. We also consider presenting the information content using SysML.

IV. FINDINGS

A. Findings on Classification (Q1)

We survey five studies, [3], [5], [6], [7], and [10]. To the best of our knowledge, these studies include the majority of the relevant information on the subject.

Two classification criteria are defined in [5]. The first (C1) is where track processing is performed. According to C1, track processing can be: 1) *central level* (observations are sent from sensors to remote processors for joint formation of global tracks), 2) *sensor level* (local tracks formed by local processors attached to sensors are sent to remote processors which perform track-to-track fusion to obtain global tracks), and 3) *hybrid* (combination of central and local level processing).

The other criterion (C2) is where the track file (database) is formed and maintained. According to C2, track file maintenance can be: 1) *centralized* (track file is maintained by a single central processor), and 2) *distributed* (track file is maintained by multiple distributed processors).

Classification criterion used in [3] is connectedness of communication graph (C3). By this criterion, architecture can be: 1) *singly connected* (there is only one communication path from each sensor to each processor), and 2) *multiply connected* (there are multiple communication paths from at least one sensor to at least one processor).

Reference [5] describes six architecture types: 1) central-level tracking with centralized track file (BP-CTCF), 2) central-level tracking with distributed track file (BP-CTDF), 3) sensor-level tracking with centralized track file (BP-STCF), 4) sensor-level tracking with centralized track file and feedback (BP-STCFF), 5) sensor-level tracking with distributed track file (BP-STDF), and 6) hybrid (BP-H).

Reference [6] describes eight architecture types: 1) distributed tracking with reporting responsibility (MB-DTRR), 2) p**u**re central-level composite tracking (MB-UCCT), 3) p**r**actical central-level composite tracking (MB-RCCT), 4) distributed tracking with central-level track fusion (MB-DTCF), 5) distributed tracking with distributed track fusion (MB-DTDF), 6) distributed tracking with central-level track fusion and tracklets (MB-DTCFT), 7) distributed tracking with distributed track fusion and tracklets (MB-DTDFT), and 8) distributed composite tracking (MB-DCT).

Nine architecture types are described in [3]: 1) centralized (CCM-C), 2) decoupled (CCM-D), 3) replicated centralized (CCM-RC), 4) hierarchical without feedback (CCM-H), 5) hierarchical with sensor sharing (CCM-HSS), 6) hierarchical with feedback (CCM-HF), 7) peer-to-peer with neighbors (CCM-PPN), 8) broadcast (CCM-B), and 9) c**y**clic (CCM-Y).

Four architectures are identified in [7]: 1) track-to-track fusion (RT-TTF), 2) centralized tracking (RT-CT), 3) equivalent measurement architecture (RT-EMA), and 4) local track measurement architecture (RT-LTMA).

Surprisingly, a recent survey on MSDF for IoT [10], almost completely neglects MSDF architectures, but focuses on mathematical methods.

In Table I, we show the classification of the architecture types according to the union of the criteria {C1, C2, C3}. The classification in Table I is one of the original contributions of this study. We found 18 different architecture types in the literature. However, some of them were labeled differently by different authors, leading to 27 different labels. Equality between architecture types with different labels is denoted with equality sign in Table I.

It can be seen from Table I, that there are twelve classes, of which four are empty, two contain a single type, while six contain multiple types.

B. Findings on Optimal Selection (Q2)

Although references [3], [5], [6], and [7] do not explicitly treat the architecture realization selection as a MOO problem, seven objectives can be identified from their analyses.

TABLE I
CLASSIFICATION OF MSDF ARCHITECTURE TYPES

C1 - Track processing	**C3 - Communication graph connectedness**	**C2 - Track file maintenance**	
		Centralized	*Distributed*
Central-level	*Singly connected*	CCM-C = MB-UCCT = BP-CTCF = RT-CT	CCM-D; CCM-RC; BP-CTDF
	Multiply connected		
Local-level	*Singly connected*	CCM-H = MB-DTCF = BP-STCF = RT-TTF	MB-DTDF = BP-STDF MB-DTRR
	Multiply connected	CCM-HSS; CCM-HF = BP-STCFF	CCM-PPN; CCM-B; CCM-Y;
Hybrid	*Singly connected*	MB-RCCT = RT-LTMA; MB-DTCFT; BP-H; RT-EMA	MB-DTDFT; MB-DCT
	Multiply connected		

To those objectives, we add three more, which we deem relevant, to form the list of objectives shown in Table II. Objectives are labeled O1 – O10, and for each of them it is noted should it be maximized (MAX) or minimized (MIN). Italicized objectives (O8 – O10) have not been considered in the existing literature.

While energy-efficiency may not be a crucial objective for multi-sensor systems like ATC radar networks, it certainly is important for emerging multi-sensor systems, like WSN or IoT, which often rely on battery-operated sensors.

Size, weight and power (SWaP) cannot be ignored as objectives when designing multi-sensor systems relying on emerging mobile platforms, like unmanned aerial vehicles, which have limits on size, weight and power consumption of their payloads. Reducing SWaP is also important for systems relying on large numbers of ubiquitous sensors, like IoT and WSN.

Reduction of financial cost is important when designing any system.

The decision space for the MSDF architecture realization selection problem has not been studied explicitly in the literature. As we explain in the second section, realization implements a type, and has numbers of sensors and processors specified. Therefore, the architecture type and the number of processors should be decision variables. On the other hand, the number of sensors is not a variable, but an input parameter for the problem. Since communication graphs can be hierarchical, the number of levels of hierarchy should also be a decision variable.

In Table III, we show our proposal on the decision variables for the architecture realization selection problem, assuming that the number of sensors is fixed. For each variable it is noted is it a scalar or a vector. The decision space definition presented in Table III is one of the original contributions of this study.

In Fig. 1, Fig. 2, Fig. 3, and Fig. 4, we show the communications graphs of four examples of MSDF architecture realizations, i.e. four decision space points, for a system utilizing four sensors.

Fig. 2 and Fig. 3 illustrate that, in a four sensor system, there are at least two ways to utilize the hierarchical without feedback (CCM-H) architecture type. It is intuitively clear that when the number of sensors increases, there will be an increased number of ways to arrange the processors in a hierarchical tree graph.

Large number of objectives and a decision space whose cardinality increases with the number of sensors indicate that the subject problem is not trivial, having in mind emerging systems with large numbers of sensors. Multi-objective approach would certainly help the decision makers to better understand the possible trade-offs.

TABLE II
OBJECTIVES OF THE MSDF ARCHITECTURE REALIZATION SELECTION

Objective	**Optimization Goal**
O1 – Assessment accuracy	MAX
O2 – Misalignment correction complexity	MIN
O3 – Latency	MIN
O4 – Robustness / survivability	MAX
O5 – Computational requirements	MIN
O6 – Communication bandwidth requirements	MIN
O7 – Implementation complexity	MIN
O8 – Energy-efficiency	MAX
O9 – Size, weight and power (SWaP)	MIN
O10 – Financial cost	MIN

TABLE III
DECISION VARIABLES FOR THE MSDF ARCHITECTURE REALIZATION SELECTION PROBLEM

Variable	**Category**
V1 – Number of levels of hierarchy	Scalar
V2 – Number of processors for each hierarchy level	Vector
V3 – Architecture type for each hierarchy level	Vector

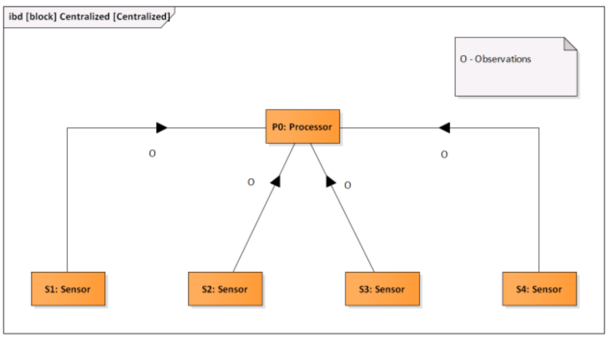

Figure 1. Example of a MSDF architecture realization for a four sensor system. Decision variables have the following values: V1 = 1, V2 = {1}, V3 = {CCM-C}.

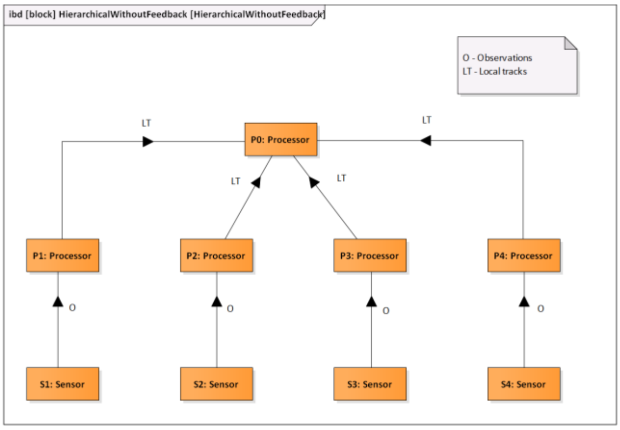

Figure 2. Example of a MSDF architecture realization for a four sensor system. Decision variables have the following values: V1 = 2, V2 = {4, 1}, V3 = {CCM-H, CCM-H}.

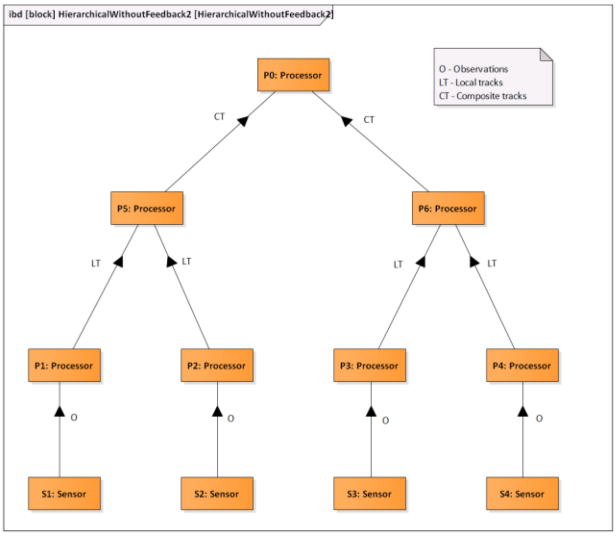

Figure 3. Example of a MSDF architecture realization for a four sensor system. Decision variables have the following values: V1 = 3, V2 = {4, 2, 1}, V3 = {CCM-H, CCM-H, CCM-H}.

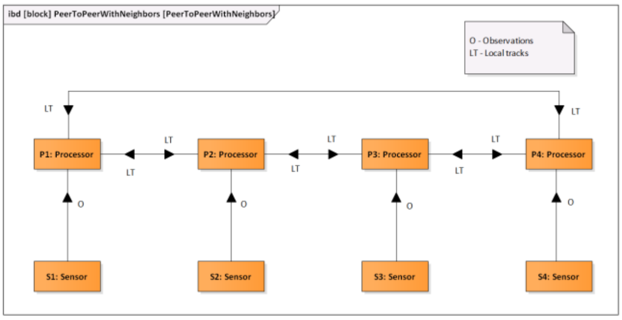

Figure 4. Example of a MSDF architecture realization for a four sensor system. Decision variables have the following values: V1 = 1, V2 = {4}, V3 = {CCM-PPN}.

C. Findings on Presentation (Q3)

Fig. 1, Fig. 2, Fig. 3, and Fig. 4 illustrate how communication graphs can be presented by means of SysML internal block diagram (IBD), while the information content can be depicted by means of SysML item flow notation. Fig. 5 shows how information graph can be presented using SysML activity diagram.

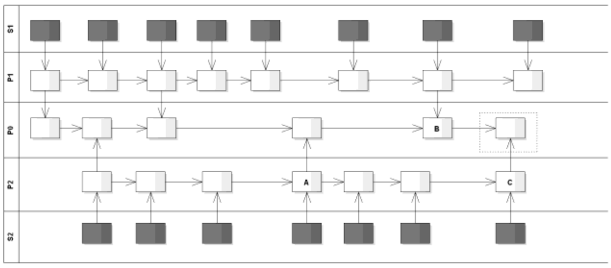

Figure 5. SysML activity diagram showing the information graph of a MSDF architecture realization for a two sensor system, with decision variables having the following values: V1 = 2, V2 = {2, 1}, V3 = {CCM-H, CCM-H}.

V. CONCLUSION

MSDF architecture is one of the key concerns in the design of a multi-sensor system. The landscape of multi-sensor systems has changed recently, thanks to emergence of multi-sensor systems based on large number of resource constrained sensors, such as WSN or IoT.

Three criteria for MSDF architecture type classification were proposed in existing studies, but neither of the studies used all of the three. This study combines all of the three criteria to provide more complete architecture type taxonomy. However, it is possible that the criteria could be refined further, which is a potential subject of future work.

Selection of a MSDF architecture realization for a particular system is a non-trivial MOO problem. We identify ten objectives, three of which were not considered previously, presumably because they were not significant for traditional multi-sensor systems. We propose the decision variables, and notice how the decision space size increases with the number of sensors. Emergence of systems based on large number of resource constrained sensors increases the complexity of the problem, by introducing new objectives, such as energy-efficiency and SWaP, and by increasing the size of the decision space. Proposed objective and decision spaces are at high level of abstraction, and require elaboration, mathematical formulation, and testing on particular problems.

This study proposes a way how SysML can be used to present all elements of a MSDF architecture realization. While such use of SysML may be obvious for some researchers and practitioners, we deem that it should be documented.

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