On the Definition of Information Fusion as a Field of Research

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Abstract – A more precise definition of the field of information fusion can be of benefit to researchers within the field, who may use such a definition when motivating their own work and evaluating the contribution of others. Moreover, it can enable researchers and practitioners outside the field to more easily relate their own work to the field and more easily understand the scope of the techniques and methods developed in the field. Previous definitions of information fusion are reviewed from that perspective, including definitions of data and sensor fusion, and their appropriateness as definitions for the entire research field are discussed. Based on strengths and weaknesses of existing definitions, a novel definition is proposed, which is argued to effectively fulfill the requirements that can be put on a definition of information fusion as a field of research.

Keywords: information fusion, definition

1 Introduction

During the last decade a substantial amount of research has been dedicated to problems concerning how to combine – or fuse – data from multiple sources in order to support decision making. Traditionally there has been a focus on fusing online sensor data, but more recent work also considers other sources, such as databases, simulations, ontologies, text documents, the web, and even humans. The research has addressed both human decision makers, who are supported by the underlying fusion systems, and automated decision making without human intervention.

The term *information fusion* has become a well-established name for the research field concerned with this type of problems, which is not least reflected in the names of the annual international conference on information fusion, and the two journals *Information Fusion – an International Journal on Multi-Sensor, Multi-Source Information Fusion*, and *Journal of Advances in Information Fusion*. However, as important as having such an informative name of the field is to have a definition that clearly states the main research problems of the field.

A precise definition may be important for practitioners whose interest in applying techniques developed in the field may increase with a better understanding of the type of problems addressed by these techniques. Furthermore, such a definition would also allow researchers outside the area to more easily relate their own research to the field of information fusion, and thereby allow for a higher degree of cross-fertilization between the different fields. It should be stressed that equally important to being able to conclude that something is indeed a contribution to the field, is being able to determine what is *not* a contribution – a too loose definition would allow the inclusion of only vaguely related topics, with minor relevance to the field as a whole. Hence, such a definition could clearly also play an important role for researchers already inside the field, who have to motivate the relevance of their own work as well as evaluate the contributions of others to the area.

In this paper, we review previous definitions of information fusion, also including definitions of *data and sensor fusion*, which sometimes are considered to be special cases of, and sometimes synonyms for, information fusion [1]. Based on the limitations of these when it comes to defining the field of research, we suggest a novel definition, which is more inclusive in some respects compared to several of the earlier definitions, but at the same time can be used to more clearly conclude what is not considered to be a contribution to the field of research.

Our motivation for this work is twofold and can be broken down into a 'global' and a 'local' component. The first one is that with this conference celebrating its tenth anniversary the field of information fusion could be said to have come of age. Thus it might be time to take stock and assess which disciplines are contributing to the field as it currently is, and which other disciplines or research fields would we want or need to contribute to information

fusion in the future. This is dependent on currently open and unresolved issues, many of which information fusion researchers presumably did not even consider ten years ago. The second reason is more personal and more pragmatic, namely that two years ago we embarked on establishing an interdisciplinary information fusion research program at the University of Skövde. The program currently involves almost 50 academic researchers, as well as about 50 industrial collaborators, and has a relatively broad scope, ranging from traditional information fusion research areas, such as ground situation awareness in a military context [2] to relatively novel application areas, such as bioinformatics [3] and manufacturing [4]. Naturally this makes it important for us to be clear about what information fusion is for us – and what it is not – and how it relates to other areas of research.

In the next section, we present and discuss the previous definitions with respect to three general criteria. In section three, we present and motivate the novel definition and discuss whether it fulfills the requirements one may put on a description of the research field. Finally, in section four we give some concluding remarks and outline directions for future research.

2 Definitions of Sensor, Data and Information Fusion

In this section we first present a number of earlier definitions of sensor, data and information fusion. We then discuss them in the light of some criteria that can be used for evaluating candidate definitions of the research field.

2.1 Previous Definitions

It should be noted that only a few of the definitions below actually try to define a field of research, but most of them define these terms as being processes. These are nevertheless included here since they with only little modification in principle could serve as a definition for the research field (e.g., "Information fusion is a research field concerned with the study of processes for ...").

JDL (1987)
Data fusion is "a process dealing with the association, correlation, and combination of data and information from single and multiple sources to achieve refined position and identity estimates, and complete and timely assessments of situations and threats, and their significance. The process is characterized by continuous refinements of its estimates and assessments, and the evaluation of the need for additional sources, or modification of the process itself, to achieve improved results." [5]

Hugh Durrant-Whyte (1988)
"The basic problem in multi-sensor systems is to integrate a sequence of observations from a number of different sensors into a single best-estimate of the state of the environment." [6]

Llinas (1988)
"Fusion can be defined as a process of integrating information from multiple sources to produce the most specific and comprehensive unified data about an entity, activity or event. This definition has some key operative words: specific, comprehensive, and entity. From an information–theoretic point of view, fusion, to be effective as an information processing function, must (at least ideally) increase the specificity and comprehensiveness of the understanding we have about a battlefield entity or else there would be no purpose in performing the function." [7]

Richardson and Marsh (1988)
"Data fusion is the process by which data from a multitude of sensors is used to yield an optimal estimate of a specified state vector pertaining to the observed system." [8]

McKendall and Mintz (1988)
"...the problem of sensor fusion is the problem of combining multiple measurements from sensors into a single measurement of the sensed object or attribute, called the parameter." [9]

Waltz and Llinas (1990)
"This field of technology has been appropriately termed data fusion because the objective of its processes is to combine elements of raw data from different sources into a single set of meaningful information that is of greater benefit than the sum of the contributing parts.

As a technology, data fusion is actually the integration and application of many traditional disciplines and new areas of engineering to achieve the fusion of data." [10]

Luo and Kay (1992)
"Multisensor fusion, ..., refers to any stage in an integration process where there is an actual combination (or fusion) of different sources of sensory information into one representational format." [11]

Abidi and Gonzalez (1992)
"Data fusion deals with the synergistic combination of information made available by various knowledge sources such as sensors, in order to provide a better understanding of a given scene." [12]

Hall (1992)
"Multisensor data fusion seeks to combine data from multiple sensors to perform inferences that may not be possible from a single sensor alone." [13]

DSTO (1994)
Data fusion is "a multilevel, multifaceted process dealing with the automatic detection, association, correlation, estimation, and combination of data and information from single and multiple sources." [14]

Malhotra (1995)
"The process of sensor fusion involves gathering sensory data, refining and interpreting it, and making new sensor allocation decisions." [15]

Hall and Llinas (1997)
"Data fusion techniques combine data from multiple sensors, and related information from associated databases, to achieve improved accuracy and more specific inferences than could be achieved by the use of single sensor alone." [16]

Goodman, Mahler and Nguyen (1997)
Data fusion is to "locate and identify many unknown objects of many different types on the basis of different kinds of evidence. This evidence is collected on an ongoing basis by many possibly allocatable sensors having varying capabilities" and to "analyze the results in such a way as to supply local and over-all assessments of the significance of a scenario and to determine proper responses based on those assessments." [17]

Paradis, Chalmers, Carling and Bergeron (1997)
"Data fusion is fundamentally a process designed to manage (i.e., organize, combine and interpret) data and information, obtained from a variety of sources, that may be required at any time by operators or commanders for decision making. ... data fusion is an adaptive information process that continuously transforms available data and information into richer information, through continuous refinement of hypotheses or inferences about real-world events, to achieve a refined (potentially optimal) kinematics and identity estimates of individual objects, and complete and timely assessments of current and potential future situations and threats (i.e., contextual reasoning), and their significance in the context of operational settings." [18]

Starr and Desforges (1998)
"Data fusion is a process that combines data and knowledge from different sources with the aim of maximising the useful information content, for improved reliability or discriminant capability, while minimising the quantity of data ultimately retained." [19]

Wald (1998)
"Data fusion is a formal framework in which are expressed means and tools for the alliance of data of the same scene originating from different sources. It aims at obtaining information of greater quality; the exact definition of greater quality will depend upon the application." [20]

Evans (1998)
"The combining of data from different complementary sources (usually geodemographic and lifestyle or market research and lifestyle) to 'build a picture of someone's life'". [21]

Wald (1999)
"Data fusion is a formal framework in which are expressed the means and tools for the alliance of data originating from different sources." [22]

Steinberg, Bowman and White (1999)
"Data fusion is the process of combining data to refine state estimates and predictions." [23]

Gonsalves, Cunningham, Ton and Okon (2000)
"The overall goal of data fusion is to combine data from multiple sources into information that has greater benefit than what would have been derived from each of the contributing parts." [24]

Hannah, Ball and Starr (2000)
"Fusion is defined materially as a process of blending, usually with the application of heat to melt constituents together (OED), but in data processing the more abstract form of union or blending together is meant. The 'heat' is applied with a series of algorithms which, depending on the technique used, give a more or less abstract relationship between the constituents and the finished output." [25]

Llinas (2001)
"Information fusion is an Information Process dealing with the association, correlation, and combination of data and information from single and multiple sensors or sources to achieve refined estimates of parameters, characteristics, events, and behaviors for observed entities in an observed field of view. It is sometimes implemented as a Fully Automatic process or as a Human-Aiding process for Analysis and/or Decision Support." [1]

Dasarathy (2001)
"Information fusion encompasses the theory, techniques, and tools conceived and employed for exploiting the synergy in the information acquired from multiple sources (sensor, databases, information gathered by humans etc.) such that the resulting decision or action is in some sense better (qualitatively and quantitatively, in terms of

accuracy, robustness and etc.) than would be possible, if these sources were used individually without such synergy exploitation." [26]

Bloch and Hunter et al. (2001)
"…fusion consists in conjoining or merging information that stems from several sources and exploiting that conjoined or merged information in various tasks such as answering questions, making decisions, numerical estimation, etc." [27]

McGirr (2001)
"The process of bringing large amounts of dissimilar information together into a more comprehensive and easily manageable form is known as data fusion." [28]

Bell, Santos and Brown (2002)
"Sophisticated information fusion capabilities are required in order to transform what the agents gather from a raw form to an integrated, consistent and complete form. Information fusion can occur at multiple levels of abstraction." [29]

Challa, Gulrez, Chaczko and Paranesha (2005)
Multi-sensor data fusion "is a core component of all networked sensing systems, which is used either to:
- join/combine complementary information produced by sensor to obtain a more complete picture or
- reduce/manage uncertainty by using sensor information from multiple sources." [30]

Jalobeanu and Gutiérrez (2006)
"The data fusion problem can be stated as the computation of the posterior pdf [probability distribution function] of the unknown single object given all observations." [31]

Mastrogiovanni et al (2007)
"The aim of a data fusion process is to maximize the useful information content acquired by heterogeneous sources in order to infer relevant situations and events related to the observed environment." [32]

Wikipedia (2007)
"Information Integration is a field of study known by various terms: Information Fusion, Deduplication, Referential Integrity and so on. It refers to the field of study of techniques attempting to merge information from disparate sources despite differing conceptual, contextual and typographical representations. This is used in data mining and consolidation of data from semi- or unstructured resources." [33]

"Sensor fusion is the combining of sensory data or data derived from sensory data from disparate sources such that the resulting information is in some sense better than would be possible when these sources were used individually. The term better in that case can mean more accurate, more complete, or more dependable, or refer to the result of an emerging view, such as stereoscopic vision (calculation of depth information by combining two-dimensional images from two cameras at slightly different viewpoints).

The data sources for a fusion process are not specified to originate from identical sensors. One can distinguish direct fusion, indirect fusion and fusion of the outputs of the former two. Direct fusion is the fusion of sensor data from a set of heterogeneous or homogeneous sensors, soft sensors, and history values of sensor data, while indirect fusion uses information sources like a priori knowledge about the environment and human input.

Sensor fusion is also known as (multi-sensor) data fusion and is a subset of information fusion." [34]

MSN Encarta (2007)
"Data integration: the integration of data and knowledge collected from disparate sources by different methods into a consistent, accurate, and useful whole." [35]

2.2 Discussion

There are a number of criteria that one may consider a definition of a research field should fulfill in the ideal case. We consider the following three general criteria:

- Discipline, i.e., is it clear what the scientific fundaments of the research field are?
- Goal, i.e., does the definition clearly state what the goal of the research is and is it obvious what can be considered to be progress towards this goal?
- Contribution, i.e., is it clear by what means the research field approaches the goal?

2.2.1 Discipline

With only few exceptions, none of the definitions explicitly positions the field as concerning the development of artifacts (i.e., an engineering science). In principle, the information fusion process as described in several of the definitions, could equally well refer to biological systems[1], although most of them of course implicitly assume artificial systems. Only one definition actually mentions the scientific fundaments of the field: "As a technology, data fusion is actually the integration and application of many traditional disciplines and new areas of engineering to achieve the fusion of data". [8]

[1] Hall and McMullen, for example, in fact point out in [36], that the use of 'fusion' of course is not new as animals have always used a combination of different senses in order to survive.

2.2.2 Goal

Among the suggested goals one can find (cf. Section 2.1):

- "to achieve refined position and identity estimates"
- "to refine state estimates and predictions"
- "obtaining information of greater quality"
- "to infer relevant situations and events related to the observed environment"
- "maximising the useful information content, for improved reliability or discriminant capability, while minimising the quantity of data ultimately retained"
- "to perform inferences that may not be possible from a single sensor alone"
- "to provide a better understanding of a given scene"
- "the resulting decision or action is in some sense better (qualitatively and quantitatively, in terms of accuracy, robustness and etc.)"
- to obtain "information that has greater benefit than what would have been derived from each of the contributing parts"

While some of these give an indication of how to measure progress towards the goal, e.g., by estimating accuracy of predictions and estimates, or benefit for a decision maker, this is less clear in other cases, either because of a vague target (e.g., "greater quality") or because it is unclear why the entity, by which progress is to be measured, should be optimized (e.g., what is the purpose of performing inferences).

There are a number of aspects considered by some of the definitions that would further restrict the focus of the research field:

- Sources, i.e., the definition could be restricted to certain types of data or information, e.g., from sensors
- Scenario, i.e., the definition could be restricted to certain types of application or decision situation, e.g. time-critical decision making
- Type of process, i.e., the definition could be restricted with respect to certain characteristics of the fusion process, e.g., continuous refinement

2.2.3 Contribution

Almost all definitions indicate that progress towards the goal is to be achieved by combining information from multiple sources. Some definitions try to characterize from where the benefit of combining information from multiple sources comes, as expressed in phrases such as "...than would be possible, if these sources were used individually" and "...that has greater benefit than what would have been derived from each of the contributing parts". The problem with these definitions is that it is not clear what the alternative to combining the information from multiple sources is. One possible interpretation is that the alternative is to use only one of the sources, and these definitions would hence state that the benefit of information fusion comes from that more information can be obtained by multiple sources than a single source, something which also seems to be implied by "...than could be achieved by the use of single sensor alone". Such statements are however almost truisms, falsified only if the different sources provide redundant information. Another possible interpretation is that there indeed is some straightforward way of combining the information from these sources as opposed to the intended way that leads to a "...greater benefit than the sum of the contributing parts". However, it is not clear what corresponds to this straightforward way (i.e., what actually constitutes the "sum of the contributing parts"), and hence the definitions give no indication of how to measure progress. Furthermore, one could also argue that the goal of the research field should be more compelling than just trying to outperform single-source solutions or straightforward ways of combining information from multiple sources.

3 A Proposed Definition of the Research Field

In this section, we first propose a definition together with a more detailed motivation of its formulation, and then we discuss it in the light of the criteria discussed in the previous sections.

3.1 The Proposed Definition

3.1.1 Definition

"Information fusion is the study of efficient methods for automatically or semi-automatically transforming information from different sources and different points in time into a representation that provides effective support for human or automated decision making."

3.1.2 Motivation

The definition states that the field is concerned with the *transformation* of information. This term is intended to cover all possible ways of combining and aggregating to infer as well as reduce information. The transformation itself may require decisions supported by other transformations. We have chosen to emphasize that in addition to transforming information from different sources, we also include transformation of information obtained from a single source at different points in time, as for example a sensor often is conceived to persist over time. As stated earlier, sources can be of many different kinds (e.g., sensors, databases, simulations and humans). Similarly, the information can be obtained from different types of data, e.g. text, numbers, graphics and so on.

The definition further stresses that the transformation is either *automatic* or *semi-automatic*, indicating that the field indeed considers artifacts, possibly in cooperation with humans, rather than purely biological systems. The field can hence be considered belonging to the engineering sciences. This, of course, does not rule out that much might be learned from the biological and cognitive sciences regarding how different senses are integrated in biological systems (e.g., [37]).

The definition points out that the transformation of information should both be *efficient* and that it should result in *effective* support. This means that research contributions to this field should be evaluated based on:

1. Their effect on the decision-making process compared to alternative approaches.
2. The cost of achieving that effect with respect to consumption of time and other resources, as compared to alternative solutions.

3.2 Discussion

An ideal definition should first and foremost provide guidance for researchers within the field for how to make progress. We believe that the proposed definition indeed gives such guidance, since it quite clearly shows what is to be required from studies in the field:

A particular study within information fusion should according to the definition increase our understanding of what effect different methods of transforming information have on the support in different decision situations and with different sources of information, or how to achieve an effect in an efficient way. Such a study would then typically contribute to the field by providing new empirical evidence or theoretical arguments that certain methods of transforming information are superior to others for certain kinds of decision scenario, evaluation criterion, and sources. Methods that support or facilitate the transformation are also relevant here, including methods for sensor management, process adaptation, data association and alignment and infrastructure design. Studies may also contribute to the field by showing what requirements a particular decision situation puts on the methods for transforming the information.

It should be noted that the definition excludes work that brings no new knowledge regarding either the effectiveness or efficiency of different ways of transforming information, since such studies will not give any contribution to the goal of understanding what results in the most efficient and effective support.

We also believe that the proposed definition indeed can be related to by practitioners and researchers outside the field, since it – like most previous definitions – does not assume familiarity with field-specific terminology.

4 Concluding Remarks

We have summarily reviewed a large number of definitions for sensor, data and information fusion and discussed them in terms of whether or not they clearly state the goal for the research field, the scientific fundaments and in what way the field is supposed to approach the goal. Based on limitations or restrictions of earlier definitions, we have presented a novel definition that clearly points out a goal for the research field, how the field approaches the goal and also implicitly that the field can be considered an engineering science. Furthermore, we have argued that the definition can be used for clearly distinguishing what should – and what should not – be considered a contribution to the field. We also believe that researchers and practitioners outside the field can relate to the definition, which allows cross-fertilization as well as promoting interests in applying tools and techniques developed in the field.

In order to obtain a more complete understanding of the implications of the definition – including the relevance of the field for other fields and areas of application – the terms in the definition require further exploration and clarification. This includes providing more exact characterizations of the following:

1. The methods used for *transforming* information
2. The potential *sources* of information
3. The technical infrastructures to *automate* information fusion
4. The *effects* of information fusion in different decision-making situations
5. The potential decision-making *situations* for using information fusion systems

This list is by no means complete, which means that it will certainly continue to evolve as the research field advances in the coming decades.

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