Context-based information fusion: a survey and discussion

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Abstract

This survey aims to provide a comprehensive status of recent and current research on context-based Information Fusion (IF) systems, tracing back the roots of the original thinking behind the development of the concept of "context". It shows how its fortune in the distributed computing world eventually permeated in the world of IF, discussing the current strategies and techniques, and hinting possible future trends. IF processes can represent context at different levels (structural and physical constraints of the scenario, a priori known operational rules between entities and environment, dynamic relationships modelled to interpret the system output, etc.). In addition to the survey, several novel context exploitation dynamics and architectural aspects peculiar to the fusion domain are presented and discussed.

Keywords: Context, Information Fusion, Survey, State-of-the-art, Architectural aspects

1. Introduction

Terms like "context-awareness", "context-aware application" and "context-aware computing" have been the subject of an increasing research interest in the past twenty years. The importance of Contextual Information (CI) for improving system performance has been widely recognized and applied to successive generations of distributed computing models [1]. Notwithstanding this growing popularity, the context-awareness concept, namely considering, representing, and exploiting information and knowledge that does not characterize the focal element(s) of interest but the surrounding environment or current situation, had not crossed the borders of the aforementioned computing domain until the past few years. An area that has lately shown a rapidly escalating interest in CI is Information Fusion (IF). IF systems are traditionally designed to exploit observational data and a priori models and to work well in what can be defined as well-behaved conditions. However, they cannot be expected to work in problems where the "world-behaviour" is very complex and unpredictable without hard-coded knowledge, or in problems where contextual influences are important or even critical. The development of context-based fusion systems is an opportunity to improve the quality of the fused output and provide domain-adapted solutions. The understanding and principled exploitation of context in fusion systems is still very limited. Domain knowledge is generally acquired ad hoc from an expert and applied to stove-piped solutions that can hardly scale or adapt to new conditions. However, context should play a vital role at any level of a modern fusion system (taking as reference the JDL-Joint Directors of Laboratories- framework): from object recognition through physical context exploitation, to intention estimation through linguistic communication analysis. It would be the key element to gain adaptability and improved performance.

This survey aims to provide a comprehensive status of recent and current research on context-based IF systems, tracing back the roots of the original thinking behind the development of the concept of "context". It shows how its fortune in the distributed computing world eventually permeated in the world of IF, discussing the current strategies and techniques, and hinting possible future trends.

The paper is structured as follows: Section 2 discusses several existing definitions of context in the literature, highlighting the most relevant aspects for the fusion domain and the perspective taken in the analysis. Section 3 provides an overview of the most significant works exploiting CI in the fields of mobile and pervasive computing, image processing and understanding and Artificial Intelligence (AI). Section 4 gives a brief introduction to the terminology used in the JDL fusion model, and Section 5 makes use of this terminology to categorize existing works on context in the fusion domain according to the fusion processes involved. Section 6 provides some insights on a few fundamental concepts, discussing their meaning in fusion systems for Situation Assessment. Section 7 discusses some novel

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architectural design concepts that can be taken into account for developing context-aware fusion systems. Concluding remarks can be found in Section 8.

2. Definition of context

As difficult as it is to be very precise in defining "fusion" boundaries, we will see that the definitions of "context" and "contextual information" are equally difficult. Intuitively, CI could be said to be that information that "surrounds" a situation of interest in the world. It is information that aids in understanding the (estimated) situation and also aids in reacting to the situation, if a reaction is required. Devlin [2] takes this view, defining context as follows: "a feature F is *contextual* for an action A if F constrains A, and may affect the outcome of A, but is not a constituent of A". Contextual premises can thus be seen as a set of constraints to a reasoning process about a situation; Kandefer and Shapiro also define it in a constraint-based sense [3]: "the structured set of variables, external constraints to some (natural or artificial) cognitive process that influences the behavior of that process in the agent(s) under consideration". There are of course other definitions of this somewhat slippery term, such as that offered by Dey and Abowd [4], who state that context is "any information (either implicit or explicit) that can be used to characterize the situation of an entity". These definitions imply that these contextual premises are constraints to other premises that could be called "focal" to the formation of our "argument" or conclusion. For example, Kent writes that "It is the context of the situation alone which gives point and meaning to the subsequent elements of the speculation," implying that there is a situational premise that is separate from the contextually-augmented (or constrained) premises. Heuer, in the well-known work of [5] writes, "The significance of information is always a joint function of the nature of the information and the context in which it is interpreted", where he distinguishes "the (focal) information" and "the context" of it.

Here, we will use these viewpoints to develop a perspective as follows: In many problems involving interpretation and the development of meaning, there is often some focal data that is purposely collected to help in developing such understanding –in a surveillance application these are the sensor data and possibly human-based observational data. Through analysis, these data can support the formation of what we will call "focal premises" –statements (propositions) about some aspect of the "condition or situation" of interest. To the extent that separate contextual data or information are available, they too can be analyzed to form additional premises –propositions that we will call "contextual premises"– that, together with the focal premises, can lead to the formation of an "argument" –a conclusion traceable to the foundations of the joint set of these premises.

3. Origins and development of context representation and exploitation approaches

There is a vast literature on context in many diverse fields outside computer science spanning fields such as cognitive sciences, psychology, linguistics, social sciences. The beginning of years 1990s marks the start of a significant interest in the topic by researchers in computer science, even if a few pioneering works existed even before. At the end of that decade, the CONTEXT conference was started to gather researchers from diverse fields with the common binding interest in understating, modelling and exploiting CI. The reader is referred to Brézillon's survey [6] for an account of early works in many diverse fields and to [7] for a dedicated survey on works in AI.

Here we provide an overview of the selected works in the fields of mobile and pervasive computing, image processing and understanding and AI, highlighting the most relevant concepts and providing pointers for further reading. These fields have produced a significant amount of works on context, addressing and developing concepts that are now permeating in the fusion domain as will be discussed later.

3.1. Mobile and pervasive computing

The area of mobile and pervasive computing is probably the most prolific in terms of works dealing with CI. Starting at the beginning of the 1990s, and taking inspiration from earlier works in the domain of cognitive and social sciences, researchers in this field have never stopped to investigate ways of representing and reasoning about context. In this area, all revolves around the user and the services that can be provided to her/him. One fundamental contextual element here is location and the environment surrounding the user [8], even though it was clear from the beginning that context is much more than that [9]. A later and classic work by Dey, in addition to external features such as location, environment and time, included the emotional state of the user as part of the contextual elements (this aspect will be discussed in detail in Section 6). More recent works recognise the fact that context is also far from being static but is considered an "ever-changing environment composed of reconfigurable, migratory, distributed, and multiscale resources" as in [10], even though this work seems to focus more on the relations with surrounding computing resources.

The research in this field is so vast that a number of surveys exist. In addition to providing several seminal papers on the subject, in 2000 Dey surveyed the literature [4] for context-aware computing approaches according to the type of CI used (location, identity, activity and time) and the way it is exploited (for presentation, execution of a service, or tagging for later retrieval). Later, the often cited paper of Strang and Linnhoff-Popien [1] provided a survey of the most relevant current approaches to modelling context for ubiquitous computing. Without attempting to providing a definition of context, the paper reviews the approaches in the literature that could be categorized as: key-valued models, markup scheme models, graphical models, object oriented models, logic based models, and ontology based models.

The excellent survey by Baldauf et al. [11] is probably the most well-structured, reviewing in detail the existing architecture types, sensors types, context models and discussing several framework approaches.

An extensive review of all the papers published between 2000 and 2007 can be found in [12] where all the approaches are classified according to five layers: concept and research, network, middleware, application, and user infrastructure. The middleware approach, addressed by many papers in this survey, provides a convenient way of designing an interface level between the sensor/data source level and the application level, brokering all relevant contextual data sources to the correct data sinks. This type of solution is proposed in Section 7.2 as a new approach to design in a general way context-aided IF systems.

A more recent survey of context modelling and reasoning techniques for context-aware applications can be found in [13] where, after listing a set of requirements that context models and context management system should have, several techniques belonging to the three most prominent models that satisfy the requirements are reviewed: object-role based, spatial models, and ontology-based. Hybrid models, which combine different formalisms in an attempt to better fulfil the requirements, are then discussed and presented as promising direction.

Multi-agent systems have been identified as basic technology for software development in Ambient Intelligence (AmI) and pervasive computing [14], [15] to develop context-based services. So, in [16], the key technologies in AI for AmI are planning, learning, temporal reasoning and agent-oriented technologies. Another term usually associated to AmI is smart environments [17], generally involving the implementation of intelligent agents and multi-agent interactions. An example, in the assisted living domain can be seen in [18]. In other cases, as [19], the interactions and reasoning with CI in AmI environments are implemented with blackboard paradigm to increase the communication efficiency among different nodes sharing their context information to provide the services to the users.

Regarding knowledge representation and communication, reasoning with ontologies has proved to be a powerful process with advantages over classical multiagent content languages, such as FIPA Semantic Language (SL). So, ontologies have been proposed to be the knowledge representation of agent systems [20]. So, in [21] authors develop an ontology to represent the basic ideas of the contextual knowledge domain used in the communication of agents: instances or individuals which are concrete occurrences of concepts; relations, roles, or properties resulting from the inner reasoning processes developed in the agents.

A recent work [22] presents a network architecture where context elements are managed at abstract level by containers and observers, with mechanisms to subscribe and release them, and blackboard interactions to connect the nodes working complementarily on the same context elements. A case study demonstrates that the framework can deal with contextual information in an Ambient Intelligence environment, with an exemplifying scenario in a teaching environment for guiding meetings attendees.

3.2. Image processing and understanding

Lately, there has been much interest in the image processing and computer vision fields to incorporate CI in order to improve detection, classification, and understanding tasks on images and videos. The studies on the effects of context on perception and cognition in the 1970s (e.g. [23]) have attracted the interest of image processing researchers that have begun to actively turn the attention from the individual objects in the scene, to the scene itself and the relations with the objects and among the objects. In particular, among the others, the work of Torralba [24] should be mentioned as being able to convincingly stoke the interest on the subject after the initial attempts in the 1970s [25] and 1990s. In the following, we provide a concise account of some relevant works showing the exploitation of CI for different image processing tasks.

Torralba et al. presented in 2004 a work that exploits context for both scene segmentation and object detection [26]. In 2006, Avidan proposed an extension to the AdaBoost algorithm to incorporate spatial reasoning for pixel classification [27].

In [28], Jiang et al. propose a context-based concept fusion method for semantic concept detection aiming at detecting concepts in whole images/videos. The proposed approach is based on a boosted conditional random fields structure able to model inter-conceptual relationships. These relationships improve the results obtained by the independent detectors by taking into account the correlations among concepts. Starting from the idea that semantic concepts do not occur in isolation, the model allows to incorporate contextual dependencies to improve concept detection.

While [28] is an example of high-level concept detection, the majority of the works focus on object detection as in [29], also exploiting 3D scene constraints [30]. A 2007 account of on state of the art by Oliva and Torralba can be found in [31] discussing the effects of context on object recognition. For the same purpose, the "auto-context" model is proposed in [32] to automatically learn an effective context model, by computing the marginals of the posterior as classifications maps.

Even though most of the papers exploit geometric and semantic relations, an effort in categorization of the types of CI used for image processing and understating can be found in [33] citing: pixel, geometric, semantic, photogrammetric, illumination, weather, geographic, temporal and cultural context. While [34] provides a review of the different ways of using CI for object categorization in still images.

Coming to more recent works, pedestrian detection by means of a multi-scale context descriptor and iterative boosted classification algorithm is presented in [35]. New category discovery by means of Object-Graphs are proposed in [36]. The approach considers modelling the interaction between an image's known and unknown objects. The approach combines the appearances of focal objects together with context information by learning a series of classifiers. The approach is tested on object segmentation, human body configuration, and scene region labelling. A study of the tradeoffs of appearance and CI using both low and high resolution images in human and machine studies can be found in [37]. The work by Zheng et al. [38] proposes a context modelling framework without the need for prior scene segmentation or context annotation. The approach makes use of a mechanism to evaluate the usefulness of context called Maximum Margin Context and transfer learning to address the problem of limited data for training the classifiers into distinguishing focal and contextual elements.

In the distributed vision domain, multi-agent solutions have been proposed to exploit the coordination capability to manage multiple sensing nodes and improve the tracking results [39]. Here, the context of each vision node needs to be shared with the other ones perceiving the same scene (from differents point of view). For instance, the Cooperative Surveillance Multi-Agent System (CS-MAS) [40] consists of agent-based platform to support the formation of smart camera coalitions; i.e., groups of sensors able to carry out complex processing tasks and cooperate with their neighbours to build fused results of the monitored environment and improve the estimation algorithms.

3.3. Context in Artificial Intelligence

The concept of context has been studied from abstract perspective in computer science too. One of the first approximations to the formalization of the notion of context in AI is due to McCarthy [41], who proposed the extensions of logic relations to explicitly include context. So, the $ist(c, p)$ relation ("is true") relates the proposition p with context c, being p true only if context c is given. Sowa [42] extended this idea with other logical relations to connect abstract context with entities, as $dscr(x, p)$ relation, to state that p "describes" entity x. Therefore, if x is a situation, $dscr$ semantics include the relation ist. Giunchiglia [43] defines an analogous framework where the context is a subset of the complete state of an entity, and it is employed to solve a task. Some theoretical analyses have been carried out to prove that these multi-context logics are more general than original "ist"-based formalisms [44]. These approaches have been investigated later to address context modeling with ontologies in the semantic web [45], [46],[47], although the current standard languages do not provide support yet.

4. JDL model

Of the many possible ways of differentiating among types of IF functions, that of the Joint Directors of Laboratories (JDL) Data Fusion Sub-Panel has gained the greatest popularity. This "JDL Model" differentiates functions into fusion "levels" that provide an often useful distinction among IF processes that relate to the refinement of estimates for parameters of interest related to "objects", "situations", "threats" and "processes" as shown in Figure 1. Note that the figure is meant to depict either a single IF node or the aggregate processing of a suite of IF nodes that would each have similar structure; the figure is strictly a discussion aid and *not* an architecture or processing diagram. In 1998, revisions of the number of and definitions for the "levels" were proposed in [49] to (a) provide a useful categorization representing logically different types of problems, which are generally (though not necessarily) solved by different techniques; and (b) maintain a degree of consistency with the mainstream of technical usage. The proposed new definitions are as follows [48]:

- **Level 0 – Sub-Object Data Assessment:** estimation and prediction of signal/object observable states on the basis of pixel/signal level data association and characterization (this is a new level which was added to the original process model);

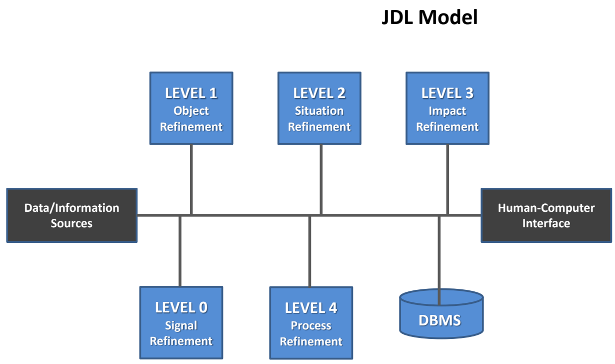

Figure 1: JDL Data Fusion Process Model derived from the 1999 revision [48].

- **Level 1 – Object Assessment:** estimation and prediction of entity states on the basis of inferences from observations;
- **Level 2 – Situation Assessment:** estimation and prediction of entity states on the basis of inferred relations among entities;
- **Level 3 – Impact Assessment:** estimation and prediction of effects on situations of planned or estimated/predicted actions by the participants;
- **Level 4 – Process Refinement (an element of Resource Management):** adaptive data acquisition and processing to support mission objectives.

As we have described the IF process here, we have noted that the inputs are from a "multisensor" front-end type capability. From a historical point of view, there is no doubt that IF system and IF technology concepts were framed around the notion that the input was sensor data. Such sensor systems were what have rather recently been called "physics-based" sensors, meaning the usual type of electromechanical devices that are designed around ideas that exploit sensory capability in some range of the electromagnetic spectrum. The idea here is to frame the observational capability of a problem-space of interest around its naturally-occurring "signals" that result either from passive emanations such as heat signals from any object or from active or responsive emanations that come from an object being illuminated by a radiating sensor such as a radar. Usually, the sensors are in either "search" mode or a directed mode, pointed to objects and spatiotemporal areas of interest. Such data of this type are focused on some collective, multisensory-based spatiotemporal Area of Interest, an AOI, which can be conceptualized as bounded by the joint spatiotemporal boundaries of the multisensory system resolutional capabilities. Our point here is that such data are usually focused on items and activities of interest and do not include any "surrounding" data or information beyond the AOI (an exception may be the possible opportunistic inference local ambient conditions with some sensors, for instance detecting meteorological conditions potentially affecting to the behavior of entities). It is true of course that an IF system design could also include supportive data base and other information peculiar to the IF processing, such as a "Track File" that maintains files on all object kinematic tracks. But at least historically (roughly, pre-year 2000 say), the data and information in an IF system design have not typically included anything of a contextual type.

We will use the definitions given here as a basis to categorize the concepts and the material found in the literature to enhance the fusion process by inclusion of contextual elements as discussed in the following sections.

5. Context in fusion

There has been active research on how to represent and exploit context in fusion processes in the past fifteen years. While recent works can be found in the Special Issue [50], and a survey on contextual tracking approaches in [51], we provide in Table 1 a breakdown of the most significant works according to JDL levels and the fusion process enhanced by CI: sensor characterization, physical and procedural constraints, prediction models, data association, tracks/algorithms management and high-level fusion.

Regarding the type of information used as context, static physical context is the most usual, such as geographic data files in Geographic Information System (GIS) with surface descriptions, bathymetry records, road maps etc. The use of tactical or procedural information besides physical is also an option, predictions can be also refined by using tactical rules, and operational domain knowledge. This is usual in the examples at higher levels. Finally, dynamic context variables such as meteorological conditions, sea state, situation variables or inputs coming from an inference engine have also been considered.

However, Table 1 shows how, save for [112] which presents a framework for the inclusion of CI in high-level fusion processes (Levels 2,3,4), all the works focus on a specific fusion process and provide a solution which applies only to specific functions. Most examples are in fact tailored to the characteristic of the problems addressed instead of general processes to design context-integrated fusion systems. No initiative has been done towards exploiting context in the fusion process in a systematic way separating context knowledge as information to be modelled and processed in the appropriate way to the fusion functions. For instance, analysis of reliability, consistency, relevance to the fusion processes, induced uncertainties etc., aspects which will be in the coming sections. As expressed instead in [115], context can play a vital role at any level of a modern fusion system: from object recognition through physical context exploitation, to intention estimation through linguistic communication analysis.

5.1. *Context sources and interaction with fusion processes*

Context-based fusion approaches can be classified in terms of the contextual knowledge sources. In many applications, it is available in static repositories such as maps, GIS databases, representations of roads, channels, bridges, etc.; in other cases, context comes through dynamic data, such as meteorological conditions. In this case we talk about context variables, implying the need of context access and update processes running in parallel with the core fusion processes. Finally, sometimes the context information cannot be observed directly, and only indirectly deduced from other sources (inferred context).

In any case, static or dynamic, we can distinguish physical and logical context. In the first case, we will have physical descriptions (like GIS files) or variables (like meteorological phenomena) which are measurable objectively. In the case of logical knowledge (such as entities engaged in a coordinated trajectory, traffic regulations, mission goals, etc), context can come from knowledge, human reports, learned from data or the result of indirect inference processes from other pieces of information. This division of context sources is illustrated in Figure 2. Therefore, a first criterion to categorize contextual sources

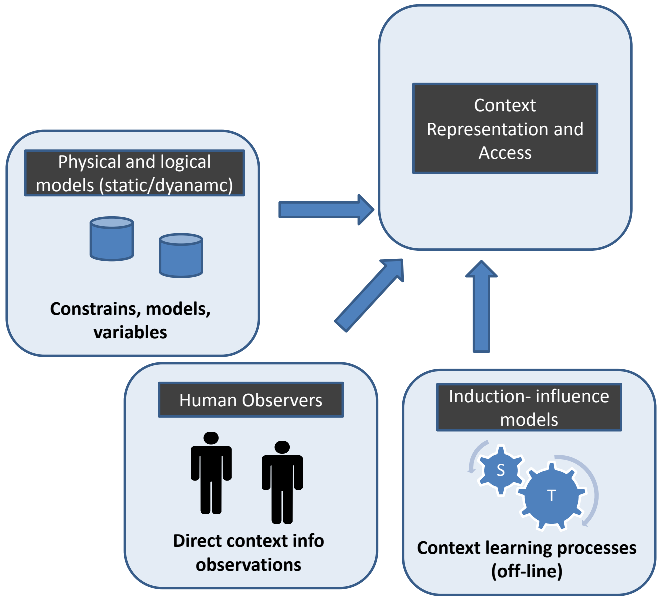

Figure 2: Context sources types.

can be in terms of the nature of available information, and observation/inference process.

Physical and logical structures.

- Static datasets with information: roads, channels, GIS databases, terrain characterization (navigation), urban environment, procedural information, normative, etc.
- Contextual variables such as physical fields: weather, wind, maritime state, clouds, etc. These variables are distribution of magnitudes, changing in space and time

Observed relations. Dynamic reports, human messages, and other documents represent the explicit input to the fusion process about situation (normal, labor day, anomaly, emergency,

High/Low	JDL level	Function	Techniques
Low	Level 0	Sensor Characterization	Geographic aspects [52, 53, 54] Weighting [55, 53, 56] Fuzzy systems [57, 58, 59]
		Signal fusion	Context Enhancement [60, 61, 62, 63]
	Level 1	Data association	Confidence-based association [64, 65, 66] JPDA [67, 68] PDAF [67] MHT [69, 70] Fuzzy association [71, 72, 73]
		Filtering	Physical and maps context [57, 74, 53] Road layout [75, 76, 77, 78, 79, 67, 80] PHD [81, 82, 78] Multiple-model [83, 84, 85, 86, 87] Non-linear filters [75, 88, 89] Tactical rules [52, 90, 81, 91]
		Track management	[92, 69]
		Classification	[93]
High	Level 2	Knowledge representation	Ontologies [94]
		Situation Assessment	Activity monitoring [95, 96, 97, 98] Situation understanding [99, 100, 101] Natural language understanding and linguistics [102, 103]
		Decision Making	[104, 105, 106, 107, 108, 109]
	Level 3	Intent assessment	[110, 111, 112]
	Level 4	Process refinement	Context discovery [113] Context adaptation [107] Context learning [82, 114, 115]

Table 1: Survey of some works exploiting context in typical fusion processes according to the JDL model.

etc.), time of the day or week (working, meeting, etc). These variables usually take discrete values indicating different contexts, coming from direct observation. The instantiated relationships are input to the system as context in some way, such as a human "observation" directly input to system.

Inferred relations. Context can be deducted as dynamic relationships. A possibility is employing an automatic inference process, which may lead to the idea of a parallel representation of context process with its own processes and sources available.

Additionally, the information in context sources can be classified as it interacts with the state variables in the estimation/inference processes, two main alternatives can be identified [116]:

Context as constraints. In many cases context imply constraints, as mentioned case of maps, channels, obstacles, routes, formal procedures, etc. Constraints can be hard physical constraints or procedural (such as forbidden operation, to be confirmed), and can be applied in different ways depending on algorithm (projection, inference rules, probabilistic conditioning such as Bayesian or Markov networks, etc). The closed-world constraint mentioned above [117] can be exploited for instance to freeze the number of players in certain domains as sport games.

Context as additional features, semantics or situation elements. In some applications context is not directly a constraint over the estimation space (in the sense of reduction in the uncertainty in the search space), but brings new problem dimensions as new features. In this case context adds dimensionality, opening hypothetical or more detailed ways to interpret the data. An example can be the knowledge of semantic features, such as presence of high-value locations, which open hypothesis to explain the trajectories of targets. In other cases, a source of context can be related with the situation that is going on, so that the meaning of available data depends on the context. An example is the detection of anomalous situations. There, a certain normal situation is defined, S, which is the normal context under these conditions (rules, characteristics, etc.). The existence of alternative known contexts would influence possible interpretations of situation, so the information about change of context to a different situation would automatically open new hypotheses.

5.2. *Low-level fusion*

The number of applications of context-aided fusion systems at low level is certainly large. In order to organize the works exploiting context in fusion, it is useful the abstraction of any fusion process as a node (Fusion Node, FN) consisting in three main basic functions applied to the data [118]. Note that the FN nominally accepts either sensor type input from some input source or an estimate (fused or otherwise formed) from some prior FN or processing node. In this characterization, the FN processing operations involve three basic functions, complemented with a management process (Figure 3):

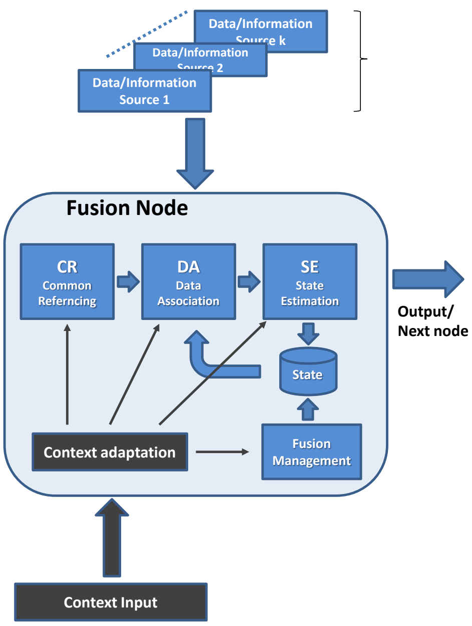

Figure 3: Fusion node and adaptation to context.

- Data alignment (also known as Common Referencing): normalization operations are performed, such as coordinate or units transformations and uncertainty transformations, to align data from information sources to be fused.

- Data association: multiple inputs of either estimates or measurements are examined in order to determine which (hypothetical) entity that the system believes to exist they are associated to or come from.

- State estimation: often about entity attributes (e.g., kinematic properties, classification attributes such as color, identity, etc), exploiting prediction models and estimation/inference processes.

- Fusion management: actions to control the output of fusion processes, such as creation, deletion, merging, etc.

So, the abundant literature is organized accordingly to the main function in the data fusion process where the context is applied: impact on sensor performance (affecting to data preprocessing), data association, estimation algorithms and track/algorithm management. Regarding the type of information used as context, several possibilities exist, as commented in previous section (physical an logical constrains, dynamic context variables, human observer, input from inference engine, etc.). In the low-level fusion, the most typical application is the use physical descriptions and domain operational knowledge, detailed in the filtering subsection.

5.2.1. Sensor characterization

The characterization of sensor performance is often depending on geographic context, an aspect that can be considered as "Level 0" accordingly to the JDL levels presented above. An example is the use of context in Vessel Traffic Services (VTS) [52]. In this case, the radar knowledge is used to discriminate between the relatively steady target returns and other returns from clutter, interference and noise. Areas of poor radar coverage and false targets are generally known. In [53], an analogous strategy is used to predict and protect the visual sensor processing with available information (for instance prediction of occluded areas).

An approach frequently used by several authors is weighting sensor input with quality factors. So, [57] proposed a method to combine symbolic and numerical information, in order to have a supervised fusion process [56, 55]. The aim is favoring measurements provided by the sensors well-adapted to the context and minimizing the impact of those sensors that are not well-adapted. For instance, in a GPS sensor the signal quality depends on the environment, it is suitable to this approach. The contextual analysis supervising tracking is able to detect the sensors, which are reliable and those, which are not. The developed algorithm automatically increases the importance of measurements of reliable sensors and decreases the importance of unreliable ones.

Fuzzy logic has been also used to represent expert knowledge to describe the reliability of the sensors [57]. In the same line, [58] and [59] present applications using fuzzy system for GPS data classification based on the signal and geometry information with fuzzy reasoning to properly weigh the observations in the Kalman filter.

5.2.2. Signal Fusion

Signal fusion is also considered as belonging to JDL "Level 0", or "early fusion", since sensor measurements are improved with a process previous to detecting entities of interest.

Our analysis of the literature, to the best of our knowledge, has not shown a significant amount of works on CI exploitation at signal level in data fusion. At least not in the terms as CI is intended here (Section 2). For instance, context is often mentioned in the remote sensing field in different processes, from pixel fusion, to change detection and region classification. However, most of the times the term "context" is used to refer to neighbouring (spatially or temporally) pixels, with respect to the one under analysis, either in the same image or in other ones possibly obtained from different sensing modalities.

The closest match can be found in what several works refer to as Context Enhancement (CE). CE is intended to be an auxiliary process aiming at improving what "surrounds" foreground objects or entities of interest. As a matter of fact, CE is used to improve the background information for different tasks such as visualization, tracking, etc. An example can be found in [60] where the image fusion techniques to automatically combine images of a scene captured under different illumination are employed. As the authors state, in addition to generating interesting non-realistic photographic effects, the technique could be used to enhance the context of night-time traffic videos for better visualization and understanding. Improvements are discussed in [61], while a multi-resolution approach is proposed in [62]. A recent comparative study on algorithms for objective assessment of multi-resolution image fusion for CE can be found in [63]. It should be noted however, that CE, as it is understood in these works, is essentially an image fusion technique and the focus is given to the quality of the resulting image [63] rather than the actual help that CE could bring to the primary fusion task (e.g. target tracking).

5.2.3. Data Association

A key fusion process where context can be applied to improve performance in low-level fusion is data association. Here, we consider fusion processes involved in tracking individual entities of interest, and therefore belonging to JDL "Level 1".

At this level, the association of sensor measurements to existing entity tracks or the initiation of new ones involves an analysis of correspondences among observations and tracked trajectories, and the context can be a boundary in the space data association process: how many interesting objects, and assignments to observations, which may take into account confidence levels obtained from context [64]. Other example is the situation of closed-world knowledge in some applications in which the objects are known to follow specific rules [65]. For instance, in sport applications such as football tracking the number of player is constrained to a certain number, where a body of knowledge is relevant for tracking the players, strategies, etc, reducing the uncertainty in the observations (video input) [66].

For instance, JPDA is a very extended association algorithm which can use context as external probabilities in the association process. [68] propose an enhancement of JPDA method based on the dynamic estimation of the detection probability of each object using a Bayesian network integrating contextual variables. Analogously, [81] use Bayesian Networks for convoy detection and improve the efficiency, computing the evolution of the detection probability (PD) at each time for each tracked object. Convoy tracking is based on the hybridization of a labelled GMCPHD (Gaussian Mixture Cardinalized Probability Hypothesis Density) and the VS-IMMC-MHT (Variable Structure Interacting Multiple Model with Constraints - Multiple Hypothesis Tracking): one is very efficient to estimate the number of targets and the other for the state estimates.

The authors in [67] apply a simple Probabilistic Data Association Filter (PDAF) where a weighted average over all feasible plot-target assignments is performed. They do a comparative analysis of information impact showing the results for a PDAF tracker including road-map and sensor information (clutter notch), only sensor information, and without any additional information.

Multiple Hypotheses Tracking (MHT) is considered a very robust method for data association. Authors in [70] use map information to prevent unnecessary branches and improve the state estimator considering the road network information. An analogous strategy is applied by [69] to boost the efficiency of the method.

Analogously, [82] propose exploiting information about context-dependent events: target births (i.e., objects entering the scene or reappearing after occlusion) and spatially persistent clutter. The information adapts a Probability Hypothesis Density (PHD) filter that spatially modulates its strength based on the learned CI.

In maritime domain, [71], [72] describe a fuzzy association strategy augmented to accommodate a variable scale target location region. Information such as bathymetric data is used to describe the influence on location possibilities of a submarine or a ship. The approach proposed is to use a weighting scheme that maps the operational parameters into the environmental reports to create a weight. The heuristic nature of information justifies the use of a fuzzy to decide weighting [73].

5.2.4. Context in Filtering

Physical and maps context. Physical context can be seen as the most direct use of context to refine state estimators, when this information is helpful to model the behavior of entities. In the case of ground systems, it is quite usual modeling geographic data in the format of GIS files ([119] [54], [77], [56]). GIS databases contain information of elevation usually in DTED format (Digital Terrain Elevation Database) expressed in geodetic coordinates, the WGS 84 system.

This has been used in ground target tracking systems [120], [57] as a priori information. This same information has been also applied in the field of navigation [89]. This is the case of or Terrain-Aided Positioning (TAP). Their base principle is to measure terrain variations along the flight path and compare it with the GIS database with terrain elevation for given positions. It is a way to avoid limitations of GPS and depend on on-board sensors as Inertial Navigation Systems (INS) or radio-altimeters. Analogously, in [75], the DGPS and INS data are fused considering also map geometry stored in a digital map database

Similar ideas can be found in maritime domain [95], [121] [64]. The geographic knowledge of the coastline, currents, tides, bathymetry, weather, sea state and ice, etc describes the marine environment when vessels move, with the addition of navigation knowledge, enables better prediction of their behaviour. For instance, deep draught vessels in shallow channels may be significantly constrained by the water depth (calculated from tabulated tidal height plus bathymetric depth). The idea of constrained estimation has been also used in maritime environment [88]: specifically, ports, coastline, sea highways and corridors, interdicted areas are elements that can be easily represented on a geographic map, providing a better understanding of the scenario.

Another example in this sea domain is con-tracker [74] which uses a representation with a field of attraction/repletion effects in each region affecting to the velocity of ships. The representation uses a grid-division map of the area of interest, used in the propagation stage, ships are affected accordingly to the field effect on velocity, using what authors call as trafficability values, based on depth information, marked channel information, restricted areas, etc

With respect to maps format, it is usual having the context represented as a set of waypoints and junctions to describe the road layout [79]. A road can be so delimited by sets of linear segments between the points [76], [77]. The possibility of constraining the estimation process has been approached by different researchers [78], [67].

A representative example is map exploitation in airport domain, a classical example in cooperative environments where the targets have available equipment (GPS or multilateration systems) to be fused with primary sources as surface movement radar [122], [123]. Targets on airport surface (aircraft, vehicles) move along the road and runway network. So, target kinematics is constrained depending on the target state: i.e. when the target is on the airport surface, its position has associated kinematic clues, such as maneuvering areas, stop and go, runway acceleration, etc.

The paradigm has been extended from ground to en-route commercial air traffic, where airways routes information are exploited, knowing that aircraft follow air routes and change their flight modes to maneuver at waypoints or Navaids. This routing information can be incorporated into the estimation process [91]. An interesting aspect, which raises theoretical considerations, concerns uncertainties, the flight mode changes usually happen around but not exactly at the waypoints. The algorithm must take into account both deterministic and stochastic factors.

Multiple-model Filters. The Kalman filter is the basic estimation algorithm to provide optimum solution if linear dynamics and Gaussian processes can be assumed. There have been different lines extending the Kalman filter to avoid this limitation, beginning with the Extended Kalman Filter (EKF), the Interacting Multiple Model Filter (IMM), the Unscented Kalman Filter (UKF), and Particle Filters (PF). IMM is recognized as a very efficient strategy to approximate optimum performance with maneuvering targets since it uses several models in parallel. With respect to the specific alternatives to integrate the ground knowledge in estimation algorithms (roads, channels, airways, etc.), they can be divided into two groups [86]: post-processing correction techniques, which run conventional tracking algorithms first and then apply corrections to the estimates to adapt them to the road knowledge; and pre-processing tracking algorithms, which incorporate the road information directly into tracking algorithms. There are several approaches in the last case: model target motion adaptively by tuning the process noise's according to the road map, project the measurements in the map, extrapolate accordingly to expected directions, etc. So, utilization of a priori knowledge requires hard-wiring the knowledge into the tracker, if possible, in order to improve the prediction model applied in the estimation process.

To include constraints, the IMM approach has been one of the most extended approaches. In this line, Variable Structure Multiple Model (VS)-IMM, has been widely used in ground target tracking [85], [83].The basic idea is that the active model set varies in an adaptive manner and thus only a small number of active models are needed to be maintained at each time. The logic manages dynamically the set of feasible dynamic models that each track can follow based on each local track context.

In an analogous way, in maritime domain, vessel route information is also used to refine dynamic models. Ships are constrained to follow the assigned channels accordingly to deep draught category and water depth. In [87] a set of motion models, and the force dictates the actuation of the specific MM. In each modeled state the force has a different effect, since the ship is likely to actuate a given motion (still anchored, navigation, approaching, etc). In [84] the state vector of the considered model is extended to include the ship state, heading, rate of turn, drift angle and velocity; etc. Among the alternatives we can mention fixed/variable structure augmented IMM Algorithm for Ship Tracking, and hybrid algorithms doing simultaneous parameter and state estimation. The hydrodynamic coefficients depend on the ship geometry, length, etc.

Predictions with Tactical Rules. Using tactical or procedural information (not only physical), target prediction can be also refined, accordingly to the operational domain. This is the case in some ground military scenarios such as convoy targets following certain tactical rules [90]. A convoy is defined in this way as a set of vehicles moving with the same dynamics during a long time. For instance, motion on the road under a limited velocity and keeping almost constant distances between them [90],[81].

The incorporation of background information allows a better discrimination and analysis of complex targets with coordinated motion. This is also usual in maritime traffic, where navigation knowledge allows accurately predict how vessels will manoeuvre as they move along shipping channels, meet other vessels and encounter. Most vessels under VTS supervision follow a known sailing plan, stay within established shipping routes and make predictable manoeuvres where channels turn or diverge. Even at a higher level, context from human reports may be also exploited [52]. Radio communications between the VTS centre and participating vessels provides information to the MTR on changes to the filed sailing plan or Estimated Time of Arrival (ETA) are similarly communicated. The MTR can also listen as vessels plan manoeuvres in response to special conditions (vessel intentions as to collision avoidance, pilot boat rendezvous, anchoring and docking).

With an analogous strategy, in air traffic domain, Liu et al. [91] model aircraft dynamics by a Stochastic Linear Hybrid System (SLHS) using a multiple-model set to describe an aircrafts dynamics with changing flight modes. Aircraft usually follow air routes and change their flight modes to maneuver at waypoints or Navaids. This routing information can be incorporated into the SLHS by the Stochastic Linear Guard Conditions (SLGC). An interesting aspect raising theoretical considerations about fusion exploitation concerns uncertainties, the flight mode changes usually happen around but not exactly at the waypoints. The SLGC can accurately account for these deterministic and stochastic factors.

Context in Non-linear Filters. Other algorithmic approach to exploit context is the particle filter in which the samples of the target state can be restricted and thus drawn exclusively from the subspace generated by the context constraints. It may follow a Bayesian strategy applied over the constrained subspace, as in [88]. PF has become very popular because of its generality keeping Bayesian approach, although its implementation opens important issues to work properly in practice. UKF also allows non-linear processes with a more efficient transformation. In order to exploit context with PF or UKF methods, hard constraints externally known are naturally integrated on the state vector or the measurement process during the estimation process [75],[89]. For instance, in [75], a constrained unscented Kalman filter is used in GPS/INS fusion integrating state constraints from the surface geometry.

Combined with multiple-mode approach, particle filters lets the different modes within the MM estimator framework be represented by constrained likelihood models, whereas the state dynamics is the same for all models. So, In [89] the Gaussian sums considered in the jump Markov systems framework solved by VS-IMM algorithms mentioned above is one important alternative in this respect.

5.2.5. Track / algorithm management

Track management can be used to exploit context in order to adapt and improve the fusion process accordingly to the situation. For instance, feedback strategies i.e. commands flowing from contextual situation level to the data fusion node, can yield improvement in adverse conditions, such as high traffic or heavy clutter scenarios with small probability of target detection. Other option is the automatic tuning or selection of algorithms (multi-algorithm fusion) based on external input [69]

As mentioned above, a decision process following a KBS approach captures the human criteria and embed this capability into the system so that it may operate autonomously. As basic capability, the inference engines carry out forward-backward chaining and truth maintenance. Data about the sensors, configuration, and environment where the entities are moving are the input to configure the KBS [92].

In [69], a rule-based Inference Engine operates with the KBS exploit knowledge bases about navigational rules, target behaviours, collision avoidance manoeuvres and interface with the tracking algorithms. An expert system is aimed at increasing robustness of sensor data fusion from disturbed sensors by adaptation of their parameters. This reaction on algorithm parameters can be quick and can correct the local anomalies as soon as they appear.

5.2.6. Classification

An example of CI exploitation for classification can be found in [93]. In the paper, CI is exploited to improve the classification of images in the medical domain by encoding context in a Bayesian framework. The authors analyse both a "compound Bayesian" approach that fuses CI for all elements in a set together and a less computationally demanding alternative that fuses only the measurements related to an object and its relevant CI. For the latter case, the authors correctly mention that CI has to be directly extracted (manually in the paper) or some form of relevance function would have to be devised in order to select the relevant context.

5.3. High-level fusion

This subsection reviews the state of the art of architectures, algorithms, and techniques developed to integrate CI in high-level fusion processes. In JDL model fusion terminology and according to the general acceptance of the term with the fusion community, the term "high" here refers to fusion levels above level 1. At these levels the fusion of data and information is largely (but not exclusively) conducted at the symbolic level [124].

5.3.1. Knowledge representation

Ontologies. An attempt in formalizing an instrument for context representation can be found in [94] where an extension to the OWL language called Context OWL (C-OWL) is presented. The enriched language allows to contextualize ontologies in the sense that contextual knowledge is not shared by default but kept local and thus not visible to the outside. C-OWL allows then for explicit mappings (bridge rules) between ontologies that enable controlled forms of global visibility. However, it must be noted that in this work the term *contexts* refers to "local models that encode a party's view of a domain" thus representing non shared models and interpretations. The work then focuses on how to establish domain relations as mappings between elements in one domain to elements in another domain. This ontology alignment is thus used to map global knowledge in local domains and vice versa.

5.3.2. Situation Assessment

Activity monitoring. Padovitz et al. propose in [99] an approach for situation classification based on Multi-Attribute Utility Theory (MAUT) sensor fusion. The technique computes a degree of support to the situation to be inferred according to the condition of the context state. The proposed method is applied to context-aware smart-spaces where readings from both environmental and user-carried devices are combined to infer situations related to the user.

The paper of Steinberg and Rogova [102] addresses the concepts of *situation* and *context* in the fields of data fusion and natural language understanding. In addition to pitching the natural language understanding problem as a Situation Assessment (SA) problem (well-known in the data fusion community), the paper has the merit of exposing the importance of contextual data in typical fusion tasks such as refining ambiguous estimates, explaining observations, and constraining processing. Also, the concepts of *context of* and *context for* are discussed with references to impacts on the interpretation and use of CI in the fusion process.

In [100], Steinberg models contexts as situations and suggests the use of Structural Equation Modeling (SEM) techniques for evaluating dependences between problem and context variables. Both types of variables can be latent or observable even though, according to Steinberg, high level fusion processes for SA mostly aim to estimate latent variables governing the situation being assessed. The concept of utility of context variables in solving a given problem is also discussed.

Rogova discusses in [101] how context plays a central role in threat assessment and crisis management by providing decision makers important information regarding the situation and its dynamics with respect to their goals. Methods and issues in context representation and discovery are described in addition to designing a processing flow for context-aware crisis management systems.

The recent work of Suarez-Tangil et al. [96] discusses typical problems in the domain of Security Information, addressed with an Event Management paradigm (SIEM) for intrusion detection with self-adaptive systems. Machine learning is applied for rule extraction to classify reported events accordingly to a context-based pattern definition of attacks. The focus is on integrating security events reported from heterogeneous sources, where context assists to the correlation process to identify related events in a complex multi-steps attack scenario.

Jenkins et al. propose in [97] a framework for aligning the uncertainty of human observations (soft data) for intelligence data analysis. The authors postulate how the error characteristics of human-generated data are significantly affected by contextual effects. Notably, the paper develops a classification scheme of human observations as relevant to the counterinsurgency domain and proposes a way to quantify the benefit of the uncertainty alignment process to the fusion tasks of data association and situation assessment.

A proposal to dynamically represent context knowledge with ontologies and evaluate anomalous situations is presented by Gomez-Romero et al. in [125]. In a harbour surveillance scenario, it arranges the architecture of the system in two processing levels. The first includes rule-based reasoning to extend tracking data and classify objects according to pre-defined categories, while in the second a belief-argumentation system (BAS) is used to determine the threat level of situations which are non-compliant to the normality model.

The recent approach of Snidaro et al. [98] discusses the fusion of uncertain sensory and contextual information for maritime situational awareness. Starting from the premise that events and anomalies are key elements in the process of assessing and understanding the observed environment, the paper arguments how building an effective situational picture for a surveillance system in the maritime domain involves combining high-level information with sensory data. The Markov Logic Networks framework is employed to both encode a priori and contextual knowledge and to fuse evidence from multiple sources, possibly reasoning over incomplete data. Knowledge is expressed by formulas in first-order logic with the possibility of associating to each of them a level of uncertainty encoded by a weight factor.

Situation understanding. Agent technologies have been applied to build fusion systems at different levels [126]. At the higher levels there are many examples, such as agents dealing with situation management or event analysis [127]. So, in [128] situation awareness is implemented with peer-to-peer multiagent system to overcome the limitations and localized knowledge of each agent platform. Since the cooperation and sharing interactions may not be predefined a priori, this leads to requirements for semantic-based agent discovery, with a service overlay approach. Sycara et al [129] propose the HiLIFE (High-Level Information Fusion Environment) fusion model for battlefield management. To these authors, context is defined as significant features that influence a situation, or expectations on what is to be observed and the interpretation of what has been observed. In order to simulate uncertain effects of actions they used the multiagent platform RETSINA (Reusable Environment for Task Structured Intelligent Networked Agents) [130].

Natural language understanding and linguistics. Ferrin et al. [103] reviews the two main contrasting paradigms on linguistic context: one considers context as a mere collection of features of the world, the other sees context as a representation of features of the world. These two main concepts represent the basis for three definitions that can be found in linguistics: objective context, pragmatic context, and discourse context. The work then proposes the use of the term *Context* to indicate a set of features at a real world physical level able to answer questions such as Who, Where, When, What, How and Why. The authors then define as *Co-text* the set of features at representational level that can be used to bind variables such as those introduced by pronouns. The term *Situation* is then used to indicate any cognitive form of link between the real world physical level and the representational one. Even though the discussion is mainly grounded in linguistic territories, the distinction between contextual elements in the real world and at representational level is seen as a significant one, worth of further analysis for the development of context-aware fusion processes.

5.3.3. Decision making

The development of information fusion systems usually imply a need for processes in support of decision making, particularly at higher levels dealing with situations and reasoning mechanisms. So, a challenge identified within the high-level fusion is related to the need to incorporate the human in the decision process [105]: "how should we design information fusion systems formed from combinations of people and machines?". This challenge reflects the concern of what is the impact of HLIF to decision support.

This aspect is proposed by some authors as "Level 5 - User Refinement" [105], the set of processes aimed at adaptive interaction and queries for data retrieval and display to support decision making and actions. Various user refinement decision support techniques have been proposed to improve decision-making, with the challenge of integrating context and culture to enrich the process. The paradigm of autonomous agents have been related with this objective [104].

Rogova et al. [106] further discuss the problem of decision making when incorporating context-dependant information in the fusion process. In particular, the paper highlights how the quality of information can, depending on the context, relate to different combinations of quality attributes. A model for sequential decision making for pattern recognition is then discussed. Quality attributes such as credibility, reliability and timeliness are considered.

Following Steinberg et al [107], the use of context for predicting and understanding situations can be oriented to establishing expectations about the states of individuals, events or situations of interest in decision-making. The use of context in data fusion can be generalized to decision-making in general to establish expectations and resolve ambiguity. Following this approach, the decision system must meet predefined mission-specific information needs in terms of user-defined Essential Elements of Information (EEIs): their current, historical and predicted location, track, identity, classification, attributes, activities, and courses of actions; interactions and other relationships.

An architecture to integrate contextual information in the fusion process for decision systems is discussed by Solaiman et al. in [108]. The framework explicitly considers the role of context as something that can produce effects on the proposed Holon functional model, the latter capturing the relationship between input and output values. To this end, and with a different meaning with respect to what is described later in Section 6, "Internal Context" is intended as intrinsic characteristics and constraints about the input-output relation (e.g. capabilities of a sensor), while "External Context" is intended as all exogenous information that can influence the relation. The application of the proposed framework is discussed with a walk-though example in the remote-sensing domain.

The work by Smirnov et al. [109] describes from a general perspective context-based knowledge fusion processes and proposes a classification related to their use in Decision Support Systems (DSS). Some general patterns are identified, analysing the effects that knowledge fusion process produces in the system for the preservation of internal structures representing the knowledge and their autonomies.

5.3.4. *Intent assessment*

Intent assessment is the process of estimating the intentions of an entity of interest. The fusion functions and processes devoted to this goal are pertinent to JDL level 3. Little and Rogova [111] claim that a formal structure of domain-specific types of entities, attributes, situations, and their relations are needed for reasoning about situations, intent and threats. To this end, they postulate the use of formal ontologies in order to capture the complexity of domain-specific knowledge so to be able to understand issues related to change over time, CI, and identity.

In a framework that encompasses different high-level fusion processes (JDL Levels 2 to 4), a model for inferring adversary intent by mapping sensor readings of opponent forces to possible opponent goals and actions is presented in [112]. In addition to extending concepts developed earlier for the use of context in intelligence processing [110], where context is seen as being able to influence the value of a situational feature of interest, context is also considered "source of expectations of what is to be observed and interpretation of what has been observed". The authors suggest that embracing a cognitive approach could benefit high level fusion processes such as inferencing and intent assessment. In particular, a terrain analysis model is used for reasoning about tactically significant operational concepts such as trafficability, engagement areas, avenues of approach.

The intent of a given entity will be later discussed in Section 6 to be its *internal context*.

5.3.5. *Process refinement*

Considered as the fourth level in JDL terminology (see Section 4), the fusion process refinement aims at dynamically adjusting and improving the fusion processes in order to better fulfil system objectives. The dynamic exploitation of context can be a key element for optimizing the fusion process as problem variables and associated context variables change (see 6). In addition, relevant contextual variables might not be known a priori so a form of dynamic context discovery should also be carried out as part of the optimization process.

A first attempt at proposing an architecture that defines the interplay of Data Fusion and Resource Management (DF&RM) functionalities in exploiting contextual information can be found in [100].

Steinberg and Bowman discuss in in [113] an evidence-accrual inference method to select context variables on the basis of their utility in refining explicit problem variables, given candidate system actions considering also their cost. They develop relations between the JDL model and Resource Management functions to accommodate adaptive decision and include adaptive context exploitation. The goal is to develop a model and an implementation scheme for seeking, discovering, selecting and fusing contextual information as part of a goal-driven decision process. This architecture allows any decision process to be completely characterized in terms of Data Fusion and Resource Management processes. Furthermore, a formal duality between Data Fusion and Resource Management functions permits reuse of techniques and consistent co-development between fusion and management processes.

Few works deal with context learning yet. The already mentioned work [82], learns targets' birth and death locations to adjust the parameters of the PHD filter. In [114] context is represented by a network of situations and the work proposes a framework for generic situation acquisition algorithm with an application to video surveillance. Learning of complex domain knowledge is discussed in [115] where also the problem of reusing contextual knowledge is addressed. In fact, transfer learning techniques are identified as a possible solution for porting the knowledge acquired in a (source) domain to another one (target domain).

6. Discussion on context in fusion

After having surveyed the literature outside and inside the fusion domain, we go back to some fundamental concepts highlighting here a few specificities that have to be taken into consideration when developing fusion systems for taking into account CI. In particular, the concepts of internal and external context can be found across many domains and we discuss here their implications in fusion systems for situational awareness.

6.1. *External and Internal context*

Among the different ways in which context has been modelled, the partition between *external* and *internal* context is a concept that appears to be widely accepted, even though there are some notable exceptions ([131] for example), as pointed out by Baldauf et al. in [11]. The authors report *internal* and *external* context as being two different dimensions separating the external physically measurable world and the internal (unobservable) state of the user including goals, tasks, emotional state, etc. This definition appears to be an adaptation for the domain of pervasive computing and context-aware devices of what was meant by earlier works in the field of cognitive science and perception. In particular, Kokinov [132] states that "context is the set of all entities that influence human (or system's) behaviour on a particular occasion, i.e. the set of elements that produce context effects". Then he describes, citing quite a few references in cognitive science dating back to years 1986, 1988 and 1993, the notions of external and internal context where the former refers to "physical and social environment or the setting within which the subjects behaviour is generated" while the latter "subjects current mental state within which the subjects behaviour is generated". In this domain external context is then seen as the sphere of subjective perceptions of the surrounding environment that have an effect on the subject's mental state. According to these definitions, a *External context→Internal context* relation appears predominant where external factors produce effects on the internal context of the subject. Although the relation is not strictly in that direction only as the internal context (e.g. mental state) of the subject can influence the correct or complete perception of the surrounding environment and thus in turn its influence can be for example, with different degrees of consciousness, altered or even prevented (Figure 4).

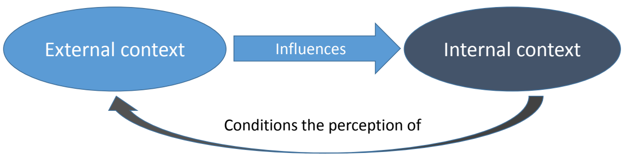

Figure 4: Relations between external and internal context in cognitive science as described in [132].

As already mentioned, these notions of internal and external context developed in the cognitive sciences domain have been quickly adopted by the researchers in mobile and pervasive computing where external attributes, most notably location, are sensed in order to provide relevant information to the user. Most of the papers concentrate on the exploitation of external context since some attributes of it can be sensed by low-cost hardware. Even though being generally non-observable, there are still some good chances of guessing the internal context of the user (of course a subset of it). Save for the cases where the user is directly providing (part of) it, for example by sharing her/his emotional state explicitly or by disclosing interests or intentions by searches in search engines, other mechanisms involve for example the analysis of web navigation patterns, opened documents, etc. [11].

A more complex situation can be found in the field of autonomous-agents. Agents typically represent human cognitive states using underlying beliefs and knowledge modelled in a knowledge representation language. So, the model of a cognitive state (internal context) defines the behaviour of agents but it strongly influenced by the perceived external context . Besides, the extension to shared context appears in a community of agents to be coordinated. For instance, Motus, Preden et al [133, 134] describe the team situation awareness concept in the context of multi-agent systems. Here, the situation awareness of an agent needs to be synchronized with the other agents, leading to the creation of this collective and distributed situation awareness.

6.2. *External and Internal context for Information Fusion*

We have seen ways of sensing or inferring external/internal context in different domains, from cognitive science to distributed agents. We would like now to highlight what are the commonalities and differences in typical tasks in the IF domain.

Uncertainty. Even though almost all of the domains surveyed can be seen in terms of IF as soon as multiple sources of data/information are present and there is the need to combine their products in order to obtain better estimates of a certain variables, typical IF systems and applications generally have the common problem of lack of direct information from the focal entities of interest. SA systems, for example, have to go through a number of processing steps, also combining heterogeneous data, in order to estimate the status and intentions (or purpose) of non-cooperative entities (or process/system) [98]. In addition, observations from sensors are generally noisy and sources of information can have different level of trust and provide outputs with different quality [135], therefore making fusion a real necessity [124].

Observed and observable context. In such a scenario, other definitions derived from Coutaz and Rey [136] can come to help. However, the definitions of situation, context, observed and observable context there provided are given with some bias towards the development of context-aware (mobile) devices, where the user is at the centre and the devices are a proxy of services between the user and the environment. We provide here a different account of a few key terms as graphically described in Figure 5.

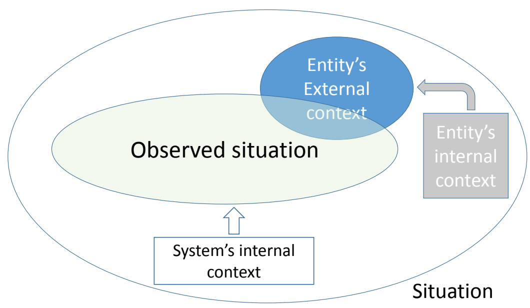

Figure 5: Situation and context.

Here we consider a working definition of a *situation* as the collection of all the entities, their attributes, the relations among them and the environment, and the events occurring in a given scenario at a certain time. The entire real situation, giving a perfect account of what is happening in the scenario, is of course impossible to observe and represent. A SA system can only observe a subset of the real underlying situation and this subset is given by the purpose of the system, that is the system's internal context. This means that if the system was designed for a specific purpose or if its current setting is directed to a certain objective, then the system is configured for observing a specific subset of the situation. This is in practice complicated even more by the sensing and interpretation capabilities of the system, the noise corrupting the observations, uncertainties involved in the processing algorithms, etc., making the situation actually observed an even smaller subset of what the system was intended to perceive and understand. Since the purpose of the system and its inner workings are known to the system designer, the internal context of the system is here understood as totally observable.

External and Internal context. An interesting notion is given in [136] is the following "context and situation can only be defined with respect to an entity for a given purpose". From this premise the authors generalize that the *Context* at time t that relates to a set of agents for performing a task is a composition of situations in a time interval between a starting time t_0 and t. A *situation* is defined as the set of values observed of the variables that relate to a given agent for performing the given task.

The specific characteristics of fusion systems for SA so far described bring us to a revision of the concepts of external and internal context as follows. If a given entity in the scenario is to be considered of interest, that is the *focal* element f, then the *external context* of f is understood here as a subset of the situation that can be put in relation with f because of its internal context. That is, the current goals and objectives of the focal element f define what could be considered as contextual for it at a given time as shown in Figure 6 thus in a sense reversing the direction of the main conditioning relation of Figure 4.

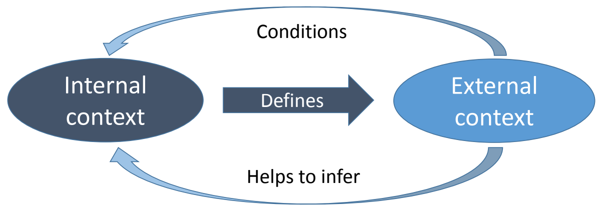

Figure 6: Typical relations between external and internal context in fusion for SA where the mission of the system is typically to infer the goals/purpose (internal context) of a focal entity. The internal context of the focal entity defines what in the current situation is contextually relevant to it (external context). This external context can be observed or inferred by the system in order to discover the entity's internal context. At the same time the external context (e.g. road network) conditions the goals of the focal entity.

Here, the goals of f (unknown and to be discovered) project a number of relations to elements of the situation that are relevant to f 1) for accomplishing its goals or 2) relevant to the system because their contextual effects on f help to understand the behaviour of f and infer its goals or purpose. This means that in a fusion system for SA both the focal's goals and CI need to be continuously estimated in a iterative process: the initially hypothesised goals of f define what is contextual to f that in turns helps to refine/confirm/reject the initial hypothesis. This proceeds, in a fashion similar to the Expectation Maximization (EM) algorithm, continuously and dynamically as f can change its goals over time, also depending on the focal's own contextual knowledge and perception of it that can influence/change its own internal context (Figure 6).

With respect to [136], the context is not intended here as a composition of situations since the valid external CI is here understood as being the one that relates to the current goals of the focal. CI that has exited the current scope of validity is treated as historical context that can be used for automatic context learning purposes.

7. Architectural aspects for context-based fusion systems

Continuing the discussion in the previous section, a fusion system may need continuous access to the available sources of external context in order to improve the estimation of the state of entities of interest. From an architectural perspective, the "middleware" concept is appealing to develop a generic, well-founded approach to connect the fusion process with available context sources in a dynamic way, adapted to the needs and inferences being carried out. In this section, we survey the middleware solutions in IF and other domains and then propose it as a solution to address the design of contex-based fusion systems in a more general way.

7.1. Middleware concept in IF and other domains

The idea of middleware is basically an abstraction to interconnect processes operating at different levels and working with diverse types of information. It is a solution to enable interaction between software systems, typically applications with different hardware/operating systems, and make uniform heterogeneous systems through software abstractions. It is associated to the concept of service-oriented computing: the information workflows are split into elementary building blocks as independent reusable services components with homogenous interfaces. So, middleware is a common term in several domains to facilitate distributed processing, connecting different applications over a network. Some examples:

- In simulation technology, middleware is a layer of software that lies between the application code and the runtime infrastructure.
- In wireless networks, middleware is the common strategy to integrate operating systems and hardware with available applications [137].
- In AmI, it is a common approach to compose context-aware services [138, 139].
- In some operating systems, middleware is used for providing multimedia services in certain environments such as automobiles or aircrafts.

In fusion systems, there have been also approaches to employ middleware architectures, such as the Network Enabled Capability (NEC) [140]. Each information fusion process involves two fundamental elements: (1) information to be fused, and (2) operations applied to the information to produce the output. Here, the access to context knowledge can be implemented as available services:

- **Information source** services are the sources of primary data to be fused.
- **Information fusion** services perform the actual fusion on the data obtained from previous information source services or other fusion services working at a lower level.

With this perspective, fusion processes can be viewed as workflows composed of different types of services, which are composed either manually by a human expert, or automatically by appropriate service composition tools. Examples of adaptive middlewares in the IF domain are Adaptive Middleware [141] and MidFusion [142]. MidFusion is an architecture to facilitate information fusion in sensor network applications. It discovers and selects the best set of sensors or sensor agents on behalf of applications (transparently), depending on the quality of service (QoS) guarantees and the cost of information acquisition, with some theoretical analysis to do selections. Adaptive Middleware is designed for context-aware applications and abstracts the applications from the sensors that provide context. The authors propose the use of utility functions to choose, given multiple alternatives for providing a specific context, the one maximizing the applications' total satisfaction. Nexus [143] is another middleware for service-oriented information fusion developed in BTs Pervasive ICT research centre. It implements the three key concepts, i.e. service-oriented computing, automated service workflow composition and peer-to-peer architecture.

7.2. Middleware proposal to integrate context sources and fusion processes

Taking this architectural perspective, a way to systematically address advanced and generic context-based IF design deals with a context access and management system, in charge of providing useful context information about the entities as a transversal independent module. Context services supporting fusion processes could include, as examples, access to reference databases, meteorological information, image repositories, GIS systems, texts, internet, etc.

The basic mechanism would be a query process (Figure 7): the middleware returns the selected relevant context information from the available sources, accordingly to hypotheses raised by fusion processes. Following the figure, two basic elements can be identified at both sides:

- At the context side, the middleware manager is responsible for collecting, updating and making contex knowledge usable by fusion processes.
- At the fusion side, the adaptation logic takes the contextual inputs and directs them to relevant fusion processes.

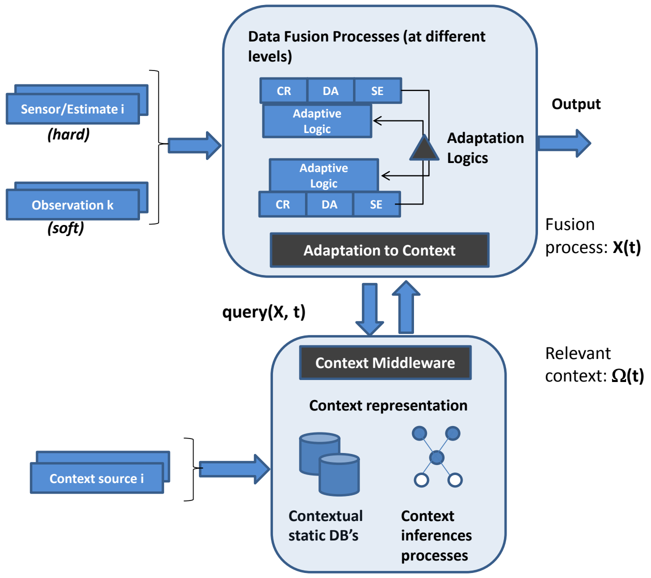

Figure 7: Context middleware mechanism.

To this end, all processes need to be designed as context-aware in order to properly exploit contextual input.

The transformation operations to be done by the context middleware are sketched in Figure 8. In order to be useful, context needs to be spatially and temporally aligned with the fusion data, adapted to the granularity of the information, and the associated uncertainty should be available.

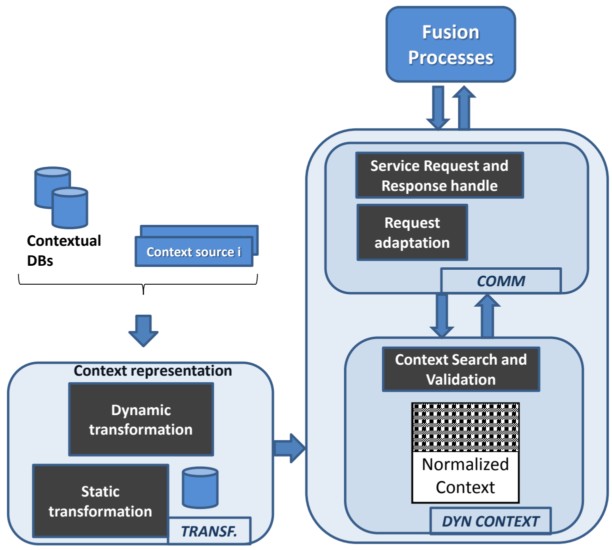

Figure 8: Context functions access.

The main operations required are enumerated next. First, regarding the search of applicable context to the fusion query ("Context Search and Validation" in the figure):

- Search of context relevant to the situation: physical (roads, bridges, channels, etc.), operational rules, etc.

- Compatibility: validate the collected information as appropriate for the query and check its compatibility (e.g. map, number of objects, etc.). In some cases, context maybe is not applicable (e.g. off-road, operational rules not met, etc.)

Regarding the transformations to get the "Normalized Context":

- Context correlation and alignment with the fusion process. This is especially relevant for the use of real-time "dynamic" contextual sources, i.e. meteorological services:
  - Spatial alignment (fundamental for efficiency): search with appropriate representation and algorithms (maps, GIS, roads, etc.)
  - Time alignment (necessary when context is dynamic): simple temporal indexing, extrapolation models, etc.
- It must provide up-to-date context. This means that it must integrate on-line information appropriate and potentially useful for the fusion processes.
- Granularity: it implies adaptation to the needs of the fusion algorithm. Some aggregation or interpolation may be required to adapt the scales at both sides.
- Characterization of the uncertainty in CI, considering both the intrinsic uncertainty in CI and the one propagated by the query (for instance uncertainty in the location to index spatial context).

At the fusion process side, it is needed the development of functions supporting the adaptation mechanisms:

- Library of alternative models that can be selected according to context (such as on/off road motion models)
- Impact on applicable models, sets of parameters, algorithms, etc.
- Applicable rules to drive the fusion processes, such as constrains, hypotheses applicable, etc.
- Closed-world models depending on situation (number of objects, appearance/disappearance assumptions, convoy motion, etc.)

Therefore, a middleware is proposed as the approach to generalize the context access and exploitation by fusion processes, organized as a set of operations done over the information available in different sources. The context middleware manager is responsible for searching and providing the relevant and updated information in the expected format and scale, considering the needs and requirements of the fusion node, so that fusion operations can take into account the context, independently of the specific strategy adopted. The service-oriented architecture is the key to develop a general perspective in the design and avoid particular solutions depending on the specific types and nature of the contextual sources available.

8. Conclusions

The exploitation of context information in fusion systems is a very active area which has been receiving increasing attention from several research communities. The idea of representing and exploiting context has been motivated in many different areas such as pervasive computing (user context to improve the services provided), image processing and AI. In the Information Fusion community, there is a growing interest in this topic, with a number of works presenting performance improvements via context exploitation in the underlying models, leading to research on powerful algorithms to exploit this additional knowledge (from non-linear filters to logic-based inference systems) and around appropriate ways to represent context. This paper surveys the state of the art in this field, taking the JDL perspective to analyse and classify the literature of existing works.

Based on this survey, the paper introduces an analysis of contextual information as determinant element to describe the behaviour of any entity. A discrimination between internal and external context from the entities' point of view is useful to describe their behaviour, and how the available external context helps in the estimation of focal entities' internal context. This discussion motivates also the architectural proposal to develop context-based fusion systems with a more general approach. Middleware is the structural element here discussed to unify context access from fusion processes, taking care of correctness and relevance accordingly to the needs of fusion tasks requiring it. Research in this architectural line, from the authors' point of view, can be an aspect to fertilize the development of a new generation of fusion systems integrating the context in a general way with solid and general theoretical foundations beyond the abundant particular cases in current literature.

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