Information Fusion 21 (2015) 173–186

Contents lists available at ScienceDirect

Information Fusion

journal homepage: www.elsevier.com/locate/inffus

Context-based multi-level information fusion for harbor surveillance

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ARTICLE INFO

Article history:
Available online 19 February 2014

Keywords:
Context
Higher-level fusion
Ontologies
Belief argumentation system
Maritime surveillance

ABSTRACT

Harbor surveillance is a critical and challenging part of maritime security procedures. Building a surveillance picture to support decision makers in detection of potential threats requires the integration of data and information coming from heterogeneous sources. Context plays a key role in achieving this task by providing expectations, constraints and additional information for inference about the items of interest. This paper proposes a fusion system for context-based situation and threat assessment with application to harbor surveillance. The architecture of the system is organized in two levels. The lowest level uses an ontological model to formally represent input data and to classify harbor objects and basic situations by deductive reasoning according to the harbor regulations. The higher level applies Belief-based Argumentation to evaluate the threat posed by suspicious vessels. The functioning of the system is illustrated with several examples that reproduce common harbor scenarios.

1. Introduction

Maritime security is an area of strategic importance for the international community. As stated in [1], "a terrorist incident against a marine transportation system would have a disaster impact on global shipping, international trade, and the world economy in addition to the strategic military value of many ports and waterways". For that reason, one of the principal goals of strengthening maritime security is to "increase maritime domain awareness" by building a "surveillance picture as complete as possible to assess the threats and vulnerabilities in the maritime realm". In particular, harbor surveillance is a critical part of maritime security procedures because of its multiple objectives: recognition of terrorist threats, prevention of maritime and ecological accidents, detection of illegal immigration, fishing and drug trafficking, and so forth. However, it is nowadays mostly developed by human operators [2], who have to evaluate an overwhelming amount of information. This makes it very difficult to keep track of the event stream with the required level of attention due to distraction, fatigue and oversight. In addition, their decisions may be strongly affected by sensor data imprecision and subjective judgment.

Next-generation harbor surveillance systems are envisioned to automatically identify potential threats with a high degree of confidence [3]. Their objective is obtaining not only tracking information about vessels, but also an abstract picture of the situation to make informed decisions. According to the JDL data fusion model, the latter task belongs to the domain of Situation Assessment, defined as the estimation of "sets of relationships among entities and their implications for the states of the related entities" [4]. In this domain, it requires understanding the intrinsic information provided by coastal sensors in the context determined by extrinsic factors, like harbor environment, operational regulations, traffic data and intelligence reports.

Recently, the increasing interest in higher-level information fusion has led to several proposals for context management – see for example the special sessions on context-based information fusion celebrated in the International Conferences on Information Fusion since 2007. Detection and characterization of activities and threats require assessing the states of situational items and their relationships within a specific context. From the perspective of the fusion process, context can be informally defined as the set of background circumstances that are not of prime interest to the system, but have potential relevance towards optimal estimation [5]. When a context is activated (i.e., some circumstances hold), more information is available to obtain and improve estimations on problem entities. This contextual information, expressed in the form of complementary knowledge or constraints, encompasses information about objects, processes, events, and relationships between them, as well as particular goals, plans, capabilities, and policies

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http://dx.doi.org/10.1016/j.inffus.2014.01.011
1566-2535/

of the decision makers. Such diversity makes formal context representation a significant challenge.

Ontologies are an appropriate formalism to represent contextual and factual knowledge in higher-level fusion [6–8]. However, ontology languages based on Description Logics, and in particular the standard ontology web language (OWL 2) [9], present several unsolved challenges when applied to Situation Assessment because: (i) they do not allow for reasoning with uncertain knowledge; and (ii) they do not directly support abductive reasoning to create and validate situational hypotheses that change in time.

In this paper we describe an Information Fusion system that uses contextual knowledge represented with ontologies to detect and evaluate anomalous situations. By contextual knowledge we mean knowledge about external information that completes, influences or constrains the situations or events of interests; e.g. physical characteristics of the environment such as terrain or weather, or knowledge about the expected behavior of the objects. The architecture of the system is arranged in two processing levels. Firstly, the system applies deductive and rule-based reasoning to extend tracking data and to classify objects according to their features. Secondly, the Belief-Argumentation System (BAS), a logic-based paradigm for abductive reasoning [10], is used in combination with the Transferable Belief Model (TBM) [11] to determine the threat level of situations involving objects that are not compliant to a normality model. A prototype implementation of this system adapted to the harbor surveillance problem is available for experimental evaluation at the authors' web page.[1]

To the best of our knowledge, this is the first attempt to combine ontologies and TBM-based uncertain reasoning to implement multi-level information fusion. Similar approaches in the literature have focused on alternative probabilistic models; namely, Multi-Entity Bayesian Networks [12,13] and Markov Logic Networks [14]. Ontologies facilitate the creation of a computable model representing complex situational context (problem entities, scenario geometry, spatial relationships, etc.), since they can be formally encoded in a logic-based expressive language. The examples show that this integrated approach reduces the number of false alarms with respect to purely ontological proposals through quantifying the threat level.

The remainder of the paper is structured as follows. In the next section, we discuss the definition and the role of context in Information Fusion. We also describe the advantages and drawbacks of common context representation formalisms, and compare our proposal with related works on ontology-based and probabilistic Situation Assessment. Section 3 studies the data sources that must be taken into account in the harbor surveillance domain, and presents the overall design of the system. Section 4 analyzes the procedures for vessel classification and abnormal situation detection. Section 5 presents a reasoning method based on the BAS for situation interpretation. Section 6 illustrates the functioning of the system in a threat detection scenario. The paper concludes with discussions on the contributions of the work and directions for future research.

2. Context and ontologies in information fusion

2.1. Context definition and representation

The Webster dictionary defines context as *"the interrelated conditions in which something exists or occurs"* or *"the parts of a discourse that surround a word or passage and can throw light on its meaning"* [15]. The concept of context has been studied in many research fields (see for example [16]). One of the first approximations to the formalization of the notion of context in Artificial Intelligence is due to McCarthy [17], who proposed the use of the relation $ist(c,p)$ to represent that a given proposition p is true in the context c. Sowa extended this theory with the $dscr(x,p)$ relation [18], which states that p describes entity x. Since x can be a situation, *dscr* semantics subsume those of *ist*. Giunchiglia defines a similar epistemological framework in which a context is a subset of the complete state of an entity that is used in reasoning to solve a task [19]. It has been proved that these multi-context logics are more general than *ist*-based formalisms [20]. These approaches have been investigated to address context modeling with ontologies in the Semantic Web, which has led to proposals including new language constructors [21–23] or annotations with specific semantics [24]. Unfortunately, they are neither widespread nor supported by the current version of the standard language OWL and associated reasoning engines.

In the Information Fusion community, context has been considered from different points of view. One of them, which in our opinion is prevalent, is to refer to external knowledge that is useful or influences the fusion processes, including background knowledge (e.g. tactics, doctrine), situation-specific knowledge (e.g. terrain), existing reports and databases, and so forth [25,26]. Sycara et al. state that part of the context are the significant features or the history of a situation that influence the features of other situation, as well as the expectations on what is to be observed and the interpretation of what has been observed [27]. They also propose the HiLIFE (High-Level Information Fusion Environment) fusion model for battlefield management. To these authors, situational context is a "*first class entity*", but not exactly in the sense of McCarthy. In their sense, it is rather a computable description of the terrain elements, the external resources and the possible inferences that is essential to support the fusion process. Our work follows the same principle. We create a model of the scenario and use background, situational and expert knowledge to drive the high-level fusion process. The specific contents of the context model for the harbor surveillance problem are described in Section 3. Context can thus be used to explain observations, to define hypotheses, to identify areas of interest to focus new data collection, to refine ambiguous estimations, and to provide for interrelationship between different fusion levels [27,28].

In [29,30], several major types of context models were considered, of which the three ones most applicable to data fusion can be characterized as key-value models, ontology-based models and logic-based models. Key-value models are the simplest way of representing context. They provide values of context attributes as environmental information and utilize exact matching algorithms on these attributes. These models may suffice for use in Level 1 fusion to work with data constraints [31], but they lack capabilities for complex context representation required by higher-level fusion. Ontology-based models provide a formal way for specifying core concepts, sub-concepts, facts and their inter-relationships to enable realistic representation of contextual knowledge [6–8]. Current approaches to ontology-based context modeling can be classified into three main areas: contextualization of ontologies, ontology design patterns, and context-aware systems [32]. Ad hoc logic-based models can be applied to extend or replace ontologies in knowledge-intensive applications. They represent context as facts and information inferred from rules. These models are generally more expressive, and allow for the development of more sophisticated representations and reasoning procedures.

The complex uncertain harbor surveillance scenario calls for a hybrid context representation combining ontology and logic-based models enriched by uncertainty consideration. We propose a fusion system in which the description of the domain entities, such as vessel types and harbor areas, the relations between them, and

[1] http://www.giaa.inf.uc3m.es/miembros/jgomez/simulator/HarborSimulator.html.