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An evidential fusion approach for activity recognition in ambient intelligence environments

Faouzi Sebbak [a,b,c,*], Abdelghani Chibani [b], Yacine Amirat [b], Aicha Mokhtari [a], Farid Benhammadi [c]

[a] Laboratory for Research in Artificial Intelligence, University of Sciences and Technology, Houari Boumediène Bab-Ezzouar, Algiers, Algeria

[b] Laboratory of Images, Signals and Intelligent Systems, University of Paris Est Créteil (UPEC), Paris, France

[c] Laboratory of Informatics Systems, Ecole Militaire Polytechnique, BP 17, Bordj-El-Bahri 16111 Algiers, Algeria

HIGHLIGHTS

- We propose to associate the conflicting context in the evidence combination rule.
- The sensor reliability participates in the conflict context acquisition.
- The proposed fusion rule is robust in highly conflicting evidences.
- The experiments show the advantages of our fusion rule over other rules.

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ABSTRACT

With the growing emergence of ambient intelligence, ubiquitous computing, sensor networks and wireless networking technologies, "ubiquitous networked robotics" is becoming an active research domain of intelligent autonomous systems. It targets new innovative applications in which robotic systems will become part of these networks of artifacts to provide novel capabilities and various assistive services anywhere and anytime, such as healthcare and monitoring services for elderly in Ambient Assisted Living (AAL) environments. Situation recognition, in general, and activity recognition, in particular, provide an added value on the contextual information that can help the ubiquitous networked robot to autonomously provide the best service that meet the needs of the elderly. Dempster–Shafer theory of evidence and its derivatives are an efficient tool to handle uncertainty and incompleteness in smart homes and ubiquitous computing environments. However, their combination rules yield counter-intuitive results in high conflicting activities. In this paper, we propose a new approach to support conflict resolution in activity recognition in AAL environments. This approach is based on a new mapping for conflict evidential fusion to increase the efficiency and accuracy of activity recognition. It gives intuitive interpretation for combining multiple sources in all conflicting situations. The proposed approach, evaluated on a real world smart home dataset, achieves 78% of accuracy in activity recognition. The obtained results outperform those obtained with the existing combination rules.

1. Introduction

With the growing emergence of ambient intelligence, ubiquitous computing, sensor networks and wireless networking technologies, "*ubiquitous networked robotics*" is becoming an active research domain of intelligent autonomous systems. It targets new innovative applications in which robotic systems will be integrated into ubiquitous computing environments as autonomous entities that are able to interact autonomously with the ambient environment and provide added value services like assisting people in smart homes, offices, buildings and public spaces. So far, robots as cognitive entities will be able to coordinate their activities with other physical or logical entities, move around, sense and explore the ambient environment, decide and act to respond to the situations they may face. These cognitive operations will become part of these networks of artifacts, to provide, individually or collectively, novel capabilities and various assistive services anywhere and anytime such as healthcare and monitoring services for elderly in Ambient Assisted Living (AAL) environments, where recognition of user's activity is needed. In activity-aware systems, human activity recognition is used for instance to detect abnormal or suspicious behavior [1,2] and provide intelligent indoor services like

* Corresponding author at: Laboratory for Research in Artificial Intelligence, University of Sciences and Technology, Houari Boumediène Bab-Ezzouar, Algiers, Algeria. Tel.: +213 21 24 79 50.
E-mail address: faouzi.sebbak@gmail.com (F. Sebbak).

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energy saving devices [3–10]. Due to uncertain or incomplete information, a naïve recognition system may report activities that are logically inconsistent with each other, e.g., the user is sleeping on the couch and at the same time is watching TV [11]. Situation recognition in the presence of incomplete or uncertain information is an important research challenges for Ubiquitous Networked Robots (UNR), especially, for decision making [12]. Situation recognition, in general, and activity recognition, in particular, provide an added value on contextual information that can help the ubiquitous networked robot to autonomously provide the best service that meet elderly person needs. The activity itself is a sequence of situations performed within time interval [8–10].

The most popular definition of context is given by Dey [13]: *Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application*. Information such as location, identity, time, and activity are considered as the primary context types for characterizing the situation of an entity. Recently, a lot of research was conducted on context representation and reasoning in order to infer situations in context-aware systems. Among evidential inference approaches, Dempster–Shafer theory of evidence is a major constituent and commonly used to handle uncertainty and incompleteness in smart homes and ubiquitous computing environments [8,9,14–17]. This theory offers a good alternative to Bayesian activity recognition methods where domain knowledge is applied [18] instead of training data that are not easily available in ubiquitous environments. However, the Dempster–Shafer theory has been mostly used with its original combination rule that may yield counter-intuitive results in high conflict [19].

The contributions of the present paper can be summarized as follows. First, we present a study of properties and performance of existing alternative combination rules for activity recognition by considering first two well-known conflict problems and second an activity dataset collected in a smart home [8]. Second, we propose a new approach to support conflict resolution in activity recognition in AAL environments. This approach is based on a new mapping for conflict evidential fusion to increase the efficiency and accuracy of activity recognition. The evidential mapping representation and reasoning provide the advantages of combining the sensed information and commonsense reasoning for activity recognition. This can increases the accuracy of decision making through resolution conflict between activities. The proposed approach is evaluated using a real world smart home dataset [8], and the obtained results outperform those obtained using the combination rules existing in the literature.

The rest of the paper is organized as follows. Section 2 gives a review of related works. Section 3 briefly presents the Dempster–Shafer (DS) theory and the existing combination rules. Based on a conflict resolution approach, Section 4 describes the proposed evidential fusion model. Section 5 reports the performance of the proposed approach for Zadeh's problem and for recognition of daily activities in AAL environment. Finally, Section 6 concludes the paper.

2. Related works

Several works are proposed in the literature in order to develop context-aware systems [13,20]. However, the incompleteness and uncertainty of contextual information, and the dynamic and heterogeneous nature of ambient intelligence environments, are open issues and challenges that need to be addressed when developing context-aware systems. A multitude of representation and reasoning approaches have been proposed in the literature. These approaches can be classified into six categories: case-based, logic-based, ontology-based, probabilistic-based, rule-based and evidential-based.

Case-based reasoning aims to infer the current situation based on the previous similar cases, i.e. similar earlier experienced situations [21–23]. It is an interesting method to address context-awareness situations and the assessment of these situations. However, its main drawback lies in how to generate automatically cases, and how to measure the similarity among them [24].

Rule-based approaches use language rules, which provide a formal model for context reasoning. In [25], the authors use the OWL (The Ontology Web Language) for rules expressing the user preferences and security constraints. However, the rule-based approaches typically cannot handle ambiguous and imperfect context information.

Logic-based context reasoning is another popular scheme that involves first-order logic. The context reasoning presented in [16] uses first order logic to represent contexts as first order predicates. It allows the deduction of higher-level context from basic sensed contexts using rule-based approaches. The approach proposed in [26] consists of a situation abstraction based on predicate logic. Loke et al. [27] use Prolog-style logic programs to represent contextual information. The Semantic Context-Aware Access Control Framework, proposed in [28], uses a hybrid reasoning approach combining Description Logic and Logic Programming reasoning. However, logic-based approaches are not suitable for reasoning about probabilistic uncertainty because they are designed for exact reasoning.

Probabilistic reasoning approaches try to predict an uncertain context by using probability theory. Gandon et al. [25] proposed an uncertainty model based on a predicate representation of contexts and associated confidence values. For reasoning about uncertainty, they incorporated various mechanisms in Gaia middleware [29] such as probabilistic logic, fuzzy logic, and Bayesian Network. The uncertainty is modeled by assigning a confidence value between 0 and 1 to predicates. In Fuzzy logic, confidence values represent degrees of membership rather than probability. Bayesian networks can be used to handle uncertainty by using existing causal relationships to perform probabilistic fusion and higher-level context aggregation [30]. Van Kasteren et al. [8] apply Hidden Markov Model (HMM) for human daily activity recognition in smart home. Brdiczka et al. [31] use HMMs for the recognition of human behavior models (i.e. activities like sitting, standing, lying, interacting with object, talking, etc.) from multimodal observation in a smart home environment. The main problem with probabilistic reasoning approaches is that it is not always possible to get training data.

Ontology-based reasoning approaches enable representation, reuse, and sharing of the semantics of context representations. A lot of works have used OWL to represent context information [32–36]. Agostini et al. [32] suggest combining rule-based reasoning with DL reasoning by proposing OWL DL ontology for context representation. The reasoning models introduced in [17,34] extend web ontology language OWL to represent dependency relations between properties. To deal with uncertain context information in ambient intelligence environments, the authors propose a probabilistic extension to an ontology-based model. It allows representing uncertain contexts by assigning probability values to context predicates and uses a Bayesian Network for reasoning about uncertainty. Then, the formal model [36] integrates Bayesian Networks into OWL to make use of probability and dependency annotated OWL to represent uncertain information. The ontological reasoning has two advantages: (1) it ensures a good integration with the ontology model; (2) it maintains low computational complexity. However, it has limited capability in dynamically inferring contexts [15].

Evidence theory [37] is considered as a prominent approach that allows inferring from imprecise and incomplete contexts in AAL environments. Zhang et al. [15] propose a context reasoning framework using extended evidence theory, along with an evidence selection and conflict resolution strategy. Hong et al. [14]