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Combining ontological and temporal formalisms for composite activity modelling and recognition in smart homes

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HIGHLIGHTS

- Hybrid activity modelling approach combining descriptions logics and temporal logic.
- Generic conceptual activity model for simple and composite activity modelling.
- Reusable activity models of activities and inference rules to infer composite activities.
- Unified mechanism for activity modelling and algorithms for simple and composite activity recognition.
- Experiments and results with average accuracy values of 100% and 88.26% for simple and composite activities, respectively.

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ABSTRACT

Activity recognition is essential in providing activity assistance for users in smart homes. While significant progress has been made for single-user single-activity recognition, it still remains a challenge to carry out real-time progressive composite activity recognition. This paper introduces a hybrid ontological and temporal approach to composite activity modelling and recognition by extending existing ontology-based knowledge-driven approach. The compelling feature of the approach is that it combines ontological and temporal knowledge representation formalisms to provide powerful representation capabilities for activity modelling. The paper describes in detail ontological activity modelling which establishes relationships between activities and their involved entities, and temporal activity modelling which defines relationships between constituent activities of a composite activity. As an essential part of the model, the paper also presents methods for developing temporal entailment rules to support the interpretation and inference of composite activities. In addition, this paper outlines an integrated architecture for composite activity recognition and elaborated a unified activity recognition algorithm which can support the recognition of simple and composite activities. The approach has been implemented in a feature-rich prototype system upon which testing and evaluation have been conducted. Initial experimental results have shown average recognition accuracy of 100% and 88.26% for simple and composite activities, respectively.
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1. Introduction

Smart Homes (SH) have been widely viewed as a promising paradigm for technology-driven assistive living for ageing population [1]. A SH can be described as a home setting augmented with a diversity of multi-modal sensors, actuators and devices along with Information and Communication Technology (ICT) based services and systems [2]. By monitoring environmental changes and inhabitant's activities, an assistive system within a SH can process sensor data, infer an inhabitant's needs and take appropriate actions to help the inhabitant perform daily living activities. As such, a SH can help older people prolong their independent living and enhance quality of life within their own homes. Generally, two types of daily living activities exist, namely, activities of daily living (ADL), and instrumental activities of daily living (IADL). ADL refers to activities concerned with taking care of one's own body. Essentially, it relates to activities that involve functional mobility (called basic ADL), and personal care (called personal ADL) [3]. IADL refers to activities concerned with interacting with the environment and as

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such they can be delegated and performed by other people in the environment [3]. In the rest of this paper, we will use ADL or activity to refer to both ADL and IADL for ease of reference.

SH inhabitants typically perform ADLs in complex patterns. For instance, an inhabitant may perform two (or more) activities in sequence or in parallel. Whenever activities are performed sequentially or in parallel, there will be underlying inter-activity dependencies among the activities involved. These inter-activity dependencies should be encoded during activity modelling so as to support activity recognition in the presence of complex activity patterns, e.g. composite activities. Applications that provide SH inhabitants with services, e.g. assistive services, should be able to correctly identify both simple and composite activities. Activity recognition is the process of tracking users and identifying the activities they are performing. It involves activity sensing, activity modelling, and activity inference. Activity sensing is responsible for monitoring users and their situated environment to obtain sensor data streams. Activity modelling creates computational activity models that are used to analyze and classify collections of sensor data into activities. Activity inference uses relevant algorithms to process sensor data against computational activity models to identify the ongoing activity.

In this paper we categorize activities as *actions*, *simple activities*, and *composite activities*. An action is an atomic (or indivisible) activity, e.g. grasping the fridge door. A simple activity is an ordered sequence of actions, e.g. preparing coffee. Finally, a composite activity is a collection of two or more simple activities occurring within a given time interval, e.g. preparing dinner and washing dishes. Composite activities can be further categorized as sequential or multi-task activities. A sequential activity is a sequence of activities that occur in consecutive time intervals, i.e., there is temporal dependency between constituent activities. A multi-task activity occurs when a single user performs two or more activities simultaneously or when multiple residents occupy a smart environment and perform activities concurrently.

Activity recognition has been widely investigated using three categories of approaches, namely, data-driven (DD) [4–8], knowledge-driven (KD) [9–13], and hybrid [14–16] activity recognition approaches. In data-driven activity recognition, activity models are learnt from pre-existing datasets using existing well-developed machine learning techniques. Activity inference is then performed against the learnt activity models whenever sensor data is obtained. In knowledge-driven activity recognition, knowledge engineers and domain experts specify activity models using a knowledge engineering process. The activity models capture commonsense and domain knowledge about activities. Artificial intelligence-based reasoning techniques are then used to infer activities from the models whenever sensor data is obtained. Hybrid activity recognition approaches combine data-driven and knowledge-driven techniques.

Simple activity recognition has been widely explored in DD [6,17–20], KD [9–11,21–23], and hybrid [13,24,25] activity recognition. However, composite activity recognition is only investigated to a limited extent in DD [4,6,8,26–28] and hybrid [14–16] activity recognition communities. In the KD activity recognition research community, the recognition of composite activities still remains largely unexplored. This challenge can be attributed to the two tasks of activity modelling and activity inference. Composite activity modelling is a challenge because activity models must capture and reason with inter-activity dependencies that are typically encoded as temporal knowledge [29]. Moreover, mechanisms are needed to process sensor data against the resulting composite activity models to infer the ongoing activities [30].

The use of ontologies in activity modelling and activity recognition has spurred interest but the focus has largely been on simple activities [9,10,31]. Ontological activity modelling can be used to define activity ontologies that describe activities and their characteristics [9,10]. The resulting activity ontologies represent activity models for mostly simple activities and support semantic reasoning for activity recognition. To support composite activity modelling and recognition, we have developed a novel activity modelling approach that combines ontologies and temporal knowledge to create activity models that represent inter-activity dependencies using temporal relationships. The approach enhances ontological activity models by adding qualitative temporal knowledge based on Allen's temporal logic relations [32]. It is worth pointing out that the study presented in this paper is contextualized in a single-resident SH environment within which the user performs both simple and composite activities.

In this paper we make a number of knowledge contributions. Firstly, we introduce a novel hybrid approach to composite activity modelling and recognition. The combination of ontological and temporal knowledge representation formalisms provides a more expressive representation formalism required for representing and modelling the complex ontological and temporal relationships of composite activities. Secondly, we develop generic activity models for composite activities based on the presented approach. This includes three core elements, namely ontological activity models, temporal activity models and entailment rules; each element models a specific aspect of composite activities. The generic models can be applied to modelling composite activities in different application scenarios. In this paper we create reusable activity models for ADLs in the context of smart homes for the purpose of illustration, testing and evaluation. Thirdly, we develop an integrated system architecture for composite activity recognition and a unified activity recognition algorithm. The algorithm can reason over sensor data streams against composite activity models to perform real-time progressive activity recognition for both simple and composite activities. In addition, we have developed a system prototype and well-designed experiments for testing and evaluation. The presented approach and associated models and methods have not been seen in related research communities.

The remainder of the paper is organized as follows. Section 2 discusses related works. Section 3 presents the hybrid approach for activity recognition. In Section 4, activity models, inference rules, and recognition algorithms are described. Section 5 presents the system prototype. The experiments and evaluation results are provided in Section 6. Finally, Section 7 concludes the paper and outlines future work.

2. Related work

In the DD activity recognition community, existing approaches capable of both simple and composite activity modelling and recognition include hidden Markov models (HMM) [6], interleaved HMM [4], factorial conditional random fields (FCRF) [26], skip-chain conditional random fields (SCCRF) [8,28,27] and mining of emerging patterns [5]. DD approaches have the ability to handle uncertain knowledge and are based on well-explored machine learning based techniques. They also have the advantage to handle temporal information that can capture short- and long-term temporal dependencies, e.g. inter-activity relationships and activity history, thereby making them suited to composite activity recognition. The main drawback is that large amounts of initial training data are needed to learn the activity models. As users perform activities in a variety of ways, all these activity variants must be present in the dataset if they are to be successfully learnt, modelled and subsequently recognized. In most cases it is difficult to obtain representative and sufficient datasets to be used for learning activity models, thus leading to the "cold start" problem. In addition, users perform activities in different manners; as a result models learnt from one user's datasets would not be reused by another user, which results in reusability problem.

KD activity recognition approaches use knowledge representation formalisms to provide explicit activity models which can be processed by artificial intelligence-based inference for activity

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