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A model of fuzzy spatio-temporal knowledge representation and reasoning based on high-level Petri nets

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A R T I C L E I N F O

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A B S T R A C T

In many application areas there is a need to represent human-like knowledge related to spatio-temporal relations among multiple moving objects. This type of knowledge is usually imprecise, vague and fuzzy, while the reasoning about spatio-temporal relations is intuitive. In this paper we present a model of fuzzy spatio-temporal knowledge representation and reasoning based on high-level Petri nets. The model should be suitable for the design of a knowledge base for real-time, multi-agent-based intelligent systems that include expert or user human-like knowledge. The central part of the model is the knowledge representation scheme called FuSpaT, which supports the representation and reasoning for domains that include imprecise and fuzzy spatial, temporal and spatio-temporal relationships. The scheme is based on the high-level Petri nets called Petri nets with fuzzy spatio-temporal tokens (PeNeFuST). The FuSpaT scheme integrates the theory of the PeNeFuST and 117 spatio-temporal relations.

The reasoning in the proposed model is a spatio-temporal data-driven process based on the dynamical properties of the scheme, i.e., the execution of the Petri nets with fuzzy spatio-temporal tokens. An illustrative example of the spatio-temporal reasoning for two agents in a simplified robot-soccer scene is given.

1. Introduction

In the past 10 years, one of the central problems in intelligent system design has been the development of appropriate knowledge-representation schemes that support spatio-temporal representation and reasoning [1–5]. These schemes have been used in different application areas such as computer vision and robot navigation [6–14], multimedia [15–18], geographical information systems (GIS) [2,19–23], natural language processing and engineering design [24], etc.

Recently, in many application domains there is a need for the development of knowledge-representation schemes that support the human-like knowledge representation of spatial, temporal and spatio-temporal information and human ways of reasoning. Most human knowledge, however, is typically expressed in vague and imprecisely defined concepts and the inference is mostly supported by common-sense and intuitive reasoning. One of the approaches to enable the representation and handling of such a type of knowledge is to introduce the concept of fuzziness [25]. Although some successful formalisms have been proposed for the separate representation of fuzzy temporal [26] or fuzzy spatial [27] data, relatively little work has been done in the field of integrated fuzzy spatio-temporal knowledge representation and reasoning.

The motivation for our research was the development of a model that allows the human-like representation of spatial, temporal and spatio-temporal information and reasoning that is suitable for the knowledge-base design used in computer-vision and robot-navigation intelligent systems based on the concepts of a multi-agent system (MAS) [28–30].

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The main goals that have to be achieved are as follows:

(i) The model has to support the design of a knowledge base that includes fuzzy and imprecise temporal, spatial and spatio-temporal relations among moving agents and/or objects. The fuzziness and imprecision related to temporal, spatial and spatio-temporal relationships have to be expressed in a form that is appropriate for human experts and users.
(ii) The model has to be appropriate for multi-agent-based systems in such a way that it enables the independent design of a knowledge base for each of the agents, and the modeling of the interactions among them.
(iii) The model has to allow a hierarchical representation and modeling of the system at different abstraction levels.
(iv) The model should be based on a well-defined formalism that allows a formal analysis of different spatial, temporal and spatio-temporal relationships among the objects (according to Ferber [28], the agents are specific objects, representing the active entities in the system), by changing the initial conditions, temporal, spatial, spatio-temporal relationships or the final goals of a modeled system.
(v) The aim of the model is the development of a knowledge base for real-time applications, meaning that the model has to support an efficacious short-time-consuming reasoning process.
(vi) The proposed model has to be suitable for the design of a program simulator based on an object-oriented programming environment.
(vii) For small or moderate-sized modeled systems the model should offer a graphical representation of the knowledge base for each of the agents.

In this paper we propose a model, the main component of which is an original fuzzy spatio-temporal knowledge representation and reasoning scheme called FuSpaT, which fulfils the above-mentioned main goals. The proposed scheme is based on an original high-level Petri net, called the Petri net with fuzzy spatio-temporal tokens (PeNeFuST). The model also includes an object-oriented simulator that contains tools for the analysis of a modeled system.

The rest of the paper is organized as follows. The related work concerning the proposed scheme is introduced in Section 2. In Section 3, we briefly describe the theoretical basis of the high-level Petri net with fuzzy spatio-temporal tokens. Section 4 presents the fuzzy spatio-temporal knowledge representation scheme called FuSpaT. In Section 5, an example of using the FuSpaT for modeling the details of a robot-soccer scene is given. The conclusion and future work are discussed in Section 6.

2. Related work

Spatio-temporal formalisms have been previously discussed in the literature. The related works concerning the proposed spatio-temporal knowledge-representation scheme can be in general divided as follows:

(i) crisp-like spatio-temporal representation models:
  - approaches that temporalize the models that are based on a spatial formalism [31,32], or vice versa [1];
  - approaches based on a description of possible changes of positions and relative orientations of the objects [4,5,24,33,34];
  - Petri net-based models [17,35–40];
  - a hybrid approach that takes into account elements from temporal logic and elements from point-set theory and point-set topology [3];

(ii) fuzzy spatio-temporal models based on the following approaches:
  - fuzzy set theory and fuzzy spatio-temporal relationships [41];
  - linguistic descriptions of the moving objects [42];
  - fuzzy-rule-based reasoning [43–45].

The brief descriptions of the related works follow. Bennett et al. [31] introduced a temporalization of the topological RCC8 calculus. Ragni and Woelfl [32] investigated a temporalization of the cardinal directions [46] in order to define a method for encoding temporized spatial constraint satisfaction problems as deterministic planning problems.

Hornsby and Egenhofer presented an approach to spatio-temporal knowledge representation based on a description of possible changes of real-world phenomena, called identifiable objects, modeled at a high level of abstraction [2]. The foundation of the model is a set of primitives and the operations that can be performed on them. These primitives are the *identity states of objects* and *transitions*. The term *object* refers to the representation of a real-world phenomenon in an information system. *Identity states* are associated with objects, capturing the notion that although an object's identity is enduring, the state of the identity may change, e.g., from existing to non-existing. The objects and their associated identities are linked through another primitive, the *transition*. The progression of an object from one state of identity to another is modeled by the transitions. The authors proposed an iconic visual language called *change description language* (CDL) to describe the changes to the identity states of objects. Although no explicitly spatial information has been incorporated into this model of change, it has been shown that tracking the changes to an object's identity over periods of existence and non-existence gives useful insights into the behavior of an object over time that are relevant to many cases of spatio-temporal change. The proposed model was used in GIS applications.

Erwig and Schneider [3] described a more explicit framework for the representation of spatio-temporal data by means of so-called *spatio-temporal predicates*. This framework is based on a hybrid approach that takes into account elements from temporal logic and elements from point-set theory and point-set topology. Presupposing a continuous model of time, they employ *temporal functions*