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Review of the Ph.D. thesis of Mr. Krystian Jobczyk

Temporal Planning with Fuzzy Constraints and Preferences

1. Introduction

The subject of the review is the Ph.D. Thesis of Mr. Krystian Jobczyk M.Sc., entitled *'Temporal Planning with Fuzzy Constraints and Preferences'. The thesis* is aimed at development of two mutually alternative approaches to the representation of temporal planning with fuzzy constraints of temporal nature and preferences. The thesis is located in Computer Science and further – Artificial Intelligence.

Planning constitutes one of the crucial forms of rational behaviour and reasoning - in particular. Planning and plan execution are the means to achieve goals; goal-oriented behaviour form the basis for rational and intelligent agent.

Intuitively, we often refer to planning as a deliberation process that chooses and organizes actions in order to achieve goals that are desired or required. Actions are executed in a given planning domain. Executing actions often modifies initial domains, i.e. the state of the world. For example, an action 'move' may change a robot/satellite position.

A natural extension of (classical) planning is temporal planning. Informally speaking, temporal planning may be viewed as classical planning which takes into account the temporal aspects. Specification of time can be understood in many ways, e.g. as a duration of action (time interval) or as temporal constraints imposed on the action materialization. *Temporal planning* is aimed at approaching different issues. The most typical are the following ones:

- time optimization of action execution (time-optimal planning),
- types of temporal constraints that may be imposed on action execution,
- representation of temporal constraints,
- construction of plans which respects temporal constraints that are required.

In general, temporal constraints are divided into two classes: the *qualitative* and *quantitative temporal constraints*.

In order to reinforce reality of investigations, temporal planning is often considered together with a new component called 'preferences'. They introduce some piece of rationality to temporal planning. Preferences may be imposed on action execution, task performing or on a choice of different components such as: situations, solutions, etc. For intuition, a plan satisfying

all temporal constraints is *admissible*, and there can be many such plans. At this point one can use preferences to select the one to be executed.

Unfortunately, temporal planning sometimes forms an acting under uncertainty. The notion of 'uncertainty' may refer to different situations in temporal planning. It may mean that our preferences were set imprecisely or that temporal constrains - imposed on action performing – are not rigid. All these situations constitute a subject of tem*poral planning with fuzzy constrains* and *preferences*.

2. Structure and contents of the dissertation

The dissertation consists of two different parts, the first one is related to representing and modelling temporal planning and fuzzy temporal constraints and preferences in terms of convolution-based models, and investigating some computational and programming-wise aspects of this convolution-based approach. The second part of the dissertation, is aimed at representing components of temporal planning - preferences, temporal constraints - in terms of some Multi-Valued Halpern-Shoham logic, modelling them by means of a newly proposed interval-based fibring semantics, and putting forward a general method of the hybrid plan controller construction exploiting the proposed approach.

Considerations of the thesis oscillate around an issue of temporal planning with different components. The thesis is also focused on methods of their modelling. The discussion is focused on formal modelling of constraints and preferences and analysis of their non-trivial properties.

The thesis is divided into two main parts: the review of selected material concerning the state-of-the-art and the presentation of the Author's contributions. The detailed content of the thesis chapters is as follows:

- ***Introduction 1.*** This chapter forms a conceptual and (partially) historical introduction to issues of temporal planning as a unique extension of classical planning. Classical planning is described in different paradigms. In particular, classical planning as graph-searching (for example, as based on STRIPS) and as satisfiability (via Davis-Putnam procedure) were discussed. Finally, temporal planning is presented as an extension of classical planning by temporal aspects of acting.
- ***Introduction 2.*** This chapter forms an introduction to temporal and fuzzy temporal constrains and their taxonomy. It also describes preferences as a separate component of temporal reasoning and temporal planning. Fuzzy temporal constraints are divided into two classes: the quantitative and the qualitative ones. The quantitative temporal constraints are briefly discussed in terms of Constraint Satisfaction Problem and its specification in the so-called *Simple Temporal Problem* (STP). The qualitative fuzzy temporal constraints - the main focus of this chapter - are properly discussed in terms of fuzzy Allen's relations. Two different approaches to their representation are presented here: Ohlbach's integral-based depiction and DeCock-Schockaer's depiction in terms of relational calculus and t-norms.
- ***Contributions. Chapter 1.*** This chapter has an intermediate character between 'Introduction 1' and 'Introduction 2' and further parts of the PhD-thesis. Different diffculties of earlier approaches to temporal planning and fuzzy temporal constraints are detected and briefly discussed. One of the difficulty is a lack of a subject-specification of temporal planning, which is usually seen in a more methodological way. It forms a motivating factor to propose an outline of a small taxonomy of a subject-problems for

temporal planning. Two classes of problems are introduced: the problems of the class of *Temporal Traveling Salesman Problem* (TTSP) and the problems of *Multi-Agent schedule-Planning Problem* (MA-SP-P). Both the paradigmatic problems (TTSP and MA-SP-P) are also defined in detail. Finally, some hints how to represent and model them are put forward in this chapter.

- ***Contributions. Chapter 2.*** This chapter introduces a new mathematical approach to fuzzy temporal constrains and preferences. At first, fuzzy Allen's relations are represented by norms of the appropriate convolutions of the Lebesgue integrable functions - in a polemic reference to Ohlbach's ideas. Secondly, a new holistic approach to fuzzy temporal constraints - on a base of the convolution representation of fuzzy Allen's relations - is elaborated. This new holistic approach forms a combination of the quantitative and the qualitative fuzzy temporal constraints. The first ones are the constraints of MA-SP-P. They are encoded in the appropriate fuzzy intervals. The qualitative ones are just fuzzy Allen's relations imposed on these fuzzy intervals.

  Next sections of the chapter present the temporal and preferential extensions of STRIPS and of Davis-Putnam procedure in a theoretic depiction. In addition, some meta-logical features of the extensions are also discussed.

  The qualitative temporal constraints are represented by Allen's relations and they are imposed on the quantitative ones. This combination allows us to introduce a new definition of *fuzzy temporal constrains* and *preferences* on a base of the last one.

- ***Contributions. Chapter 3.*** Investigations of this chapter forms a conceptual continuation of investigations of chapter 2 and they refer to computational and programming-wise aspects of fuzzy temporal constraints and their representation. At first, the convolution-based depiction of fuzzy Allen's relations is applied to STRIPS and Davis-Putnam procedure in the appropriate temporal and preferential extension. Secondly, the PROLOG-solvers for chosen cases of the Multi-Agent Schedule-Planning Problem are presented. Analyses of this chapter are carried out in the subject context of Multi-Agent Schedule-Planning Problem.

- ***Contributions. Chapter 4.*** This chapter addresses an alternative, algebraic-logical approach to representation of temporal constrains and preferences. These components are rendered in terms of a new Multi-Valued (Preferential) Halpern-Shoham logic. A 'fuzziness' is introduced here by preferences. This formal system is further interpreted in some interval-based fibred semantics. It allows us to consider combined formulas representing both preferences and actions – temporally constrained. Investigations of this chapter oscillates around Traveling Salesman Problem and its modelling.

- ***Contributions. Chapter 5.*** This chapter describes a general method of the hybrid plan controller construction and it extends a purely theoretic investigation of chapter 4 towards an application area. The controller construction runs as follows:

  1. At first, the robot motion environment is specified in Linear Temporal Logic (LTL) extended by Halpern-Shoham Logic (HS).
  2. This LTL+HS-description is encoded by the appropriate Büchi automaton and it represents a required, planned situation.
  3. Next, the second Büchi automaton is constructed for a real situation of the robot task performing.

  These two automata form a construction basis for their product automata. Its representation in terms of PROLOG plays a role of a desired plan controller.

- ***Contributions. Chapter 6.*** This chapter describes an attempt at a synthesis of earlier approaches to fuzzy temporal constraints and preferences. It is discussed here how the analysis-based and the logic-based representations might complement each other in the plan controller construction.

  For example, trajectories of agent move in a logic-based description may be interpreted as the appropriate functions in Sobolev spaces.

- ***Contributions. Chapter 7.*** This chapter contains concluding remarks and announces some promising directions of future research.

- ***Appendixes***. The thesis contains also 8 Appendixes. Appendixes 1-7 contain more advanced results from a thematic scope of the thesis, such as meta-logical features of fuzzy logic systems for Allen's relations. Appendix 8 contains a couple of mathematical definitions used in the proper body of the thesis.

3. Main Contributions of the dissertation

Novelty of the PhD-thesis may be shown as a conjunction of the following main results:

1. Two paradigmatic problems of temporal planning (Temporal Traveling Salesman Problem (TTSP) and Multi-Agent Schedule-Planning Problem (MA-SP-P)) were defined and proposed as a subject basis of temporal planning with fuzzy constraints.
2. Fuzzy Allen's relations were represented by norms from the appropriate convolutions in the appropriate space of Lebesgue integrable functions.
3. A portion of a theory for fuzzy Allen's relations in terms of real analysis and abstract algebra was elaborated.
4. A hybrid approach to fuzzy temporal constraints was elaborated on a base of fuzzy Allen's relations in terms of convolutions. (In the context of MA-SP-P.)
5. Two planning methods (STRIPS and Davis-Putnam procedure) were extended by temporal and preferential components.
6. A hybrid approach to fuzzy temporal constraints with fuzziness introduced by preferences was elaborated in terms of Preferential Halpern-Shoham logic and its fibred models. (In the context of TTSP.)
7. An outline of a construction of the plan controller was proposed on a base of the logical approach to fuzzy temporal constraints.
8. An attempt of a synthesis of these two approaches was put forward in the context of the plan controller construction. This construction is carried out in 'logical terms', but it is complemented by analytic elements (trajectories of an agent's move are represented by the appropriate functions in Sobolev's spaces.)

From a methodological point of view, this PhD-thesis showed a unique heterogeneity. It was a natural consequence of multi-dimensionality of the thesis considerations. A variety of used methods contains - for example: computational methods of measure theory and real analysis (particularly - with respect to convolution computing), formalization in terms of LTL and HS-logic, methods of construction of Bûchi automata from LTL-formulas - due to ideas of M. Vardi. These methods are also supported by some methods of logical programming - in a declarative paradigm - such as PROLOG.

In addition, some more sophisticated methods such as: The *Pavelka-Hajek's style completeness proof method* or *satisfiability checking* via reduction to the *Quantifed Boolean Formula-satisfiability* problem were presented..

4. Evaluation of the dissertation

4.1 General remarks

The dissertation concerns an important issue of substantial nature from the domain of modern computer science. The subject of the dissertation was selected in a correct way. The contents of the work are of high merits and it proves deep author's knowledge of the domain.

The first approach, presented in the thesis of Krystian Jobczyk, exploits different methods and tools of mathematical analysis to represent the so-called fuzzy Allen's relations (as a unique type of temporal constraints based on interval time representation) in a new way. These considerations are carried out in the context of Multi-Agent Planning and Scheduling Problem as a subject-basis of this analysis. The formal representation, computational and programing-wise aspects of Multi-Agent Problem are also considered.

The second proposal, put forward by the Author, represents the class of the logical approaches to the representation of temporal planning with fuzzy constraints and preferences. New results were introduced in terms of the Halpern-Shoham logic and Linear Temporal Logic. The results enable modelling of a temporally extended Traveling Salesman Problem. Finally, a construction of the controller for temporal planning was presented by means of these logical systems.

One needs to note that the main topic of the thesis and a selection of research methods fit into the current research trends in Computer Science and Artificial Intelligence, in particular. In addition, research on both the theoretic and practical aspects still constitute a promising and modern area of a scientific exploration. The methodology of the thesis is heterogeneous, but it does not constitute any shortcoming, and forms a natural consequence of (an existence of) a variety of different methods and issues in this research area. The presented mathematically well-founded in-depth analysis is unique, original, and proves the knowledge and skills of the Author.

The presented considerations are illustrated with code extracts (Prolog-based), mathematical descriptions and proofs, and several technical details of the thesis are presented in several appendixes.

4.2 Presentation, language and style

The presentation of the material is very careful, well planned, and detailed. The theoretical considerations are illustrated with a formal description of the algorithms and mathematical descriptions of the proposed models.

The technical language of the thesis is correct and confirms Author's technical expertise. On the other hand, the thesis is sometimes hard to read since the specific domain requires a deep knowledge on both mathematics and artificial intelligence, the mathematical proofs and descriptions provides some difficulties to be understand by non-experts in the area. However, all of these mathematical descriptions and proofs are technically sound and provides a formalism in the dissertation that gives an extra value to the general results showed in this work.

4.3 Minor issues and suggestions

Several minor issues and typos have been detected in the Thesis manuscript. Although these issues are always minor, and don't affect to the quality of the work, next a short description of them are given:

- The Thesis has three different introductions, a Chapter 0 that provides a short description of the motivation, the problem formulation, the objectives of thesis, etc. and other two introductions to temporal planning and temporal constraints that is a little bit confusing (it looks to be part of two different thesis works). It would be interesting to joint all of them into one general Introduction chapter.
- The thesis introductions are too focused on classical planning models as STRIPS and provide a description on PDDL and PDDL+ languages, however other more recent approaches related to probabilistic, temporal or even multi-agent planning approaches.
- Other problems, more realistic, and really close to the problem considered in this Thesis, as Vehicle Routing Problem, have not been analysed in depth.
- The examples given through the Thesis (as the blocks world example) are too simple and doesn't allow to understand how the approaches from the author could work in real domains.
- The different algorithms and methods have been carefully described from a mathematical and formal perspective. However, it is missing an analysis on the performance and scalability of those approaches in large or complex scenarios.
- The Thesis provides a List of Figures, I suggest to include a List of Tables and Acronym section (the Thesis is full of acronyms and sometimes could be difficult for the reader to remember all of them).
- The tables have no captions and they are not reference in the text.
- I suggest to include a List of Equations, for this particular type of Thesis I think is particularly relevant.
- Some figures should be resized, some of the are particularly small and difficult the readability of the work (e.g. Figures 17, 23, 1.1, 2.4, 4.1, 5.3, 5.6, 5.7).
- The Figures don't follow an uniform numbering (Figures 5.3, 1.1, 2.1, 2.2, etc. in Chapters 1 to 7, vs. Figures 1, 2, 3, … in Chapter 0). I suggest to use a common numbering.
- Figure 13 has a poor quality; it should be included as Table.
- Although the thesis is well written and the typographical standard is really good, I suggest a careful reading and revising of the final manuscript, there are some minor typos as: "adventages, cololllary, consists, contexts, corresponds, forms, fortunatelly, greather invese, modelling, nowdays, unfortunately, etc."; "A blue line represents"; "~~this~~ these relations"; "the sequence starts"; "All these facts are"; "obtained by a combinations"; "This fact approximates"; "The proper analysis is proceeding"; "it rather requires a logical". I only have a previous version of the Thesis in pdf format, so maybe part of previous typos has been currently fixed. However, I suggest to look through the text in the final Thesis version.

Previous suggestions described in this subsection are not mandatory, if possible, it would be interesting (but not necessary) to modify or include some of those suggestions in the final version of the Thesis. Despite these minor remarks detected in the Thesis work, the overall evaluation of this work is positive, and previous comments shouldn't be taken as a problem to the whole research and results obtained by the candidate during the development of his Thesis.

5. Conclusions

To sum-up, this dissertation presents numerous original and high quality contributions. The main goal of this thesis can be summarized as elaborating a new hybrid way of representing and modelling fuzzy temporal constraints and preferences in the contexts of temporal extensions of Traveling Salesman Problem and Multi-Agent Problem. The presented material concerns important research issues of applied contemporary computer science in the domain of *temporal planning* and *fuzzy temporal constraints and preferences* in terms of convolution-based models, and investigating some computational and programming-wise aspects of this convolution-based approach. Those temporal planning features have been modelled in terms of Multi-Valued Halpern-Shoham logic (based on a new proposed interval-based fibring semantics), and taking this general method to design a hybrid plan controller construction exploiting the proposed approach. The presented results contain original solutions of potential practical applications.

In conclusion, the dissertation defines and important research problem and proposes an original solution, both at the conceptual level (model, design and mathematical proofs) and at the level of implementation. It presents a deep and formal description of the different research hypothesis and obtains relevant results to the state of the art. The Author has shown an excellent general theoretical knowledge in the domain of Artificial Intelligence and he has proved possession of the ability to carry out self-reliant scientific research. The dissertation was carefully edited and satisfies all typical editorial standards.

To the best of my knowledge, the presented thesis represents very high theoretical standards and satisfies the formal and custom requirements for a PhD Thesis. In my opinion, this thesis is sufficiently mature to be considered a finished one it can be submitted for the PhD. procedure.

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