Region-Based Representation for Assistance with Spatio-Temporal Planning in Unfamiliar Environments

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Abstract

In this contribution we present a cognitively motivated approach to an interactive assistance system for spatio-temporal planning tasks. Since mental spatial problem solving is known to be based on hierarchical representations, we argue for region-based representation structures that allow for structuring a complex spatio-temporal problem such that exploring and communicating alternative solutions to a given problem are easily enabled. In this way, spatio-temporal constraints can interactively be dealt with to find appropriate solutions for a given planning problem.

Motivation

Ubiquitous assistance with spatial problem solving tasks like wayfinding from specific locations to specific other locations gained much attention in spatial cognition research (e.g., Richter & Klippel, 2005, Denis, 1997; Tversky & Lee, 1999). However, early stage route planning, i.e., pre-visiting of locations using representations of unfamiliar large-scale environments like maps has been considered in the literature only seldom (e.g., Dirlich et al., 1986).

Planning a round trip or a city tour in a foreign country are good examples for such type of problems. The problem solving task aims at selecting activities and putting them into a feasible order under consideration of temporal and spatial constraints. Temporal constraints include, for example, predefined durations of the whole trip and durations of individual activities. Spatial constraints include partially specified location assignments and distances between locations where the activities take place.

Especially in an early route planning stage, assignments of locations are specified at different levels of granularity. Location assignments can be specific places of interest (e.g., a particular museum), or regions (e.g., parts of a country, national parks, or cities). In other cases, since the environment is unfamiliar, there are no particular location assignments, but rather specific requirements on properties of the corresponding locations resulting from the type of the planned activities (e.g., swimming, hiking, or sightseeing). To solve the illustrated partially underspecified spatio-temporal planning problem means to find all possible location assignments for activities with unspecified location assignments and to obtain feasible spatio-temporal configurations (i.e., alternative solutions) which fulfill the given temporal scope and spatial constraints.

The illustrated problem solving task can be formalized as a spatio-temporal constraint satisfaction problem (cf. Dechter, 1992). However, taking into consideration all possible assignments of locations left unspecified the demonstrated task 1) has a high computational complexity, and 2) results in a large solution space. To reduce computational complexity, the search process should be guided by a human user. In doing so, significant parts of the problem space can be omitted. Yet, allowing users to participate in the search process limitations of human cognitive capacity have to be taken into consideration. Observation and comparison of a large number of alternative solutions is a cognitively demanding task (cf. Knauff et. al., 2002). Consequently, the problem space has to be adequately represented to a user in order to reduce the mental load occurring during observation and comparison of alternative solutions.

Referring to the definition by Simon (1981), "*... solving a problem simply means representing it so as to make the solution transparent*", we have to understand how humans conceive spatial and temporal information and how the intermediate problem solving states can be adequately communicated to a user. The paper describes an approach for structuring and representing a spatio-temporal problem domain which facilitates the generation of alternative solutions and provides a communication basis for collaboration of a person and an artificial assistance system.

Collaborative Assistance with Spatio-Temporal Planning

To obtain feasible solutions for the given spatio-temporal configuration problem, the constraints can be formalized as a *constraint network* (cf. Dechter, 1992). The constraint network consists of a finite set of variables, e.g., a set of activities $Conf = \{a_0, a_1, ..., a_i\}$, where $0 \leq i < \mathbf{n}$ and $\mathbf{n}$ is the number of activities, $\mathbf{n} \in N$. Each activity has the following attributes: *type*, *duration*, and *location*. Regarding the assignment of the attributes, duration is mandatory, whereas assignments of location and activity type are optional. Let the temporal interval **m** represent the duration of the whole journey. A duration of an activity a_i can be obtained by the duration function $dur\_cost(a_i)=d_i$, where $d_i \neq 0,\ d_i \in R$. An activity type is an element from $Type = \{t_0, t_1, ..t_k\}$, $k \in N$, where k is a number of activity types. A location can be a geographical position, i.e., a point with the corresponding geographical coordinates (x, y) on a 2-dimensional geographical map where one or more activities can be accomplished, or a region. Each location is associated to one or more activity types. Locations are connected with each other by paths, which have distance costs.

The constraints which may hold between the corresponding activities are expressed by the thirteen qualitative temporal relations described in (Allen, 1983). Distances between locations of activities, i.e., a function $dist\_cost(a_i, a_{i+1})$ are represented as temporal costs, i.e., time required to get from one location to another. Each feasible spatio-temporal configuration $Conf = (a_0, a_2, ..., a_i)$, where $0 \leq i < \mathbf{n}$ and $\mathbf{n}$ is the number of activities, should fulfill the following constraints: (1) The temporal relations which holds between subsequent activities a_i, a_{i+1}, where $0 \leq i < \mathbf{n}$, should be “before” (*b*) or “meets” (*m*). (2) The sum of durations and the temporal distance costs between the corresponding locations should not exceed the given temporal scope of a journey **m**, i.e., $\Sigma\, d_i + \Sigma\, dist\_cost(a_i, a_{i+1}) \leq \mathbf{m}$. (3) Underspecified spatial constraints should result in different location assignments. To obtain all feasible spatio-temporal configurations we need to search through all considerable location assignments.

Need for assistance

Since the given environment is unfamiliar and we have to deal with a large number of activities, it is difficult to solve the illustrated problem mentally. Depending on the number of unspecified location assignments the demonstrated problem is weakly constrained. Underspecified activities contribute to large solution spaces. Consequently, the provided alternative spatio-temporal configurations require mental post-processing, i.e., they have to be observed by a user in order to find a solution which corresponds to the user's specific interests and preferences.

Partially unformalized constraint systems

The demonstrated problem can be considered as a partially unformalized constraint problem (Schlieder & Hagen, 2000). The example problem solving task described in (Schlieder & Hagen, 2000) is a geometric layout constraint satisfaction problem. To provide assistance with such type of problems, they separated the constraints into formalized *hard* geometric *constraints*, e.g., ordering and alignment of elements in a spatial configuration, and s*oft constraints* like personal aesthetic preferences, which cannot be formalized. The assistance system provides users with a set of geometric configurations which fulfill the specified *hard* alignment *constraints*. Subsequently, users have to examine the generated solutions to obtain a "good" solution, which fulfills their personal requirements on solution quality regarding the personal *soft constraints*. To facilitate the mental coprocessing during the interactive search process, the introduced assistance system adapts to human reasoning strategies regarding alternative spatial configurations, i.e., reasoning with mental models (Johnson-Laird, 1983), and particularly reasoning with preferred mental models (Knauff et al., 1995).

In this vein, the demonstrated spatio-temporal planning problem can be treated likewise as a partially unformalized constraint problem, consisting of predefined spatial and temporal constraints and a user's personal interests and wishes to spend his/her time in a particular location.

However, in contrast to Schlieder and Hagen's geometric layout-problems, depending on the number of activities, we may have to deal with a greater number of objects, which have to be observed in each spatio-temporal configuration. Calculations of all possible configurations including various permutations in order of activities require much computational resources of the assisting devices. Consequently, we need a compact representation of the problem domain which on the one hand facilitates the generation of alternative solutions and on the other hand adapts to mental reasoning strategies about spatio-temporal relations.

Dealing with the complexity of geographic information

To master the computational complexity of the given spatio-temporal configuration problem we have to single out particular aspects of the problem domain, i.e., objects and specific properties and relations between them which are relevant for the problem solving task and make it possible to solve the problem efficiently (cf. Freksa & Barkowsky, 1996). Humans deal with spatial problems like route planning surprisingly well – especially in familiar environments. Therefore, organizational and structural principles of mental representations gained much attention in disciplines like cognitive psychology, artificial intelligence, and particularly in robotics. In this vein, the derived organization principles for structuring spatial information can be applied for the knowledge representations in artificial spatial systems.

The cognitively motivated principles for structuring representations of large-scale environments allow on the one hand for managing the computational complexity and on the other hand for establishing an adequate dialog between a human and an assistance system. In the following, we will describe how spatial knowledge about large-scale environments is structured in human memory and how humans operate on their mental representation when solving such types of spatial problems.

Hierarchies in Human Mind

Mental spatial knowledge representations are often described as cognitive maps (cf. Hirtle & Heidorn, 1993), cognitive atlases (cf. Hirtle, 1998), or cognitive collages (Tversky, 1993). Evidences for hierarchical representations of spatial information in human mind can be found in, e.g., (Hirtle & Jonides, 1985), (Tversky, 1993), and (Stevens & Coupe, 1978). Spatial knowledge stored in human long-term memory is often described as distorted, consisting of various loosely coupled knowledge fragments which are incomplete, inconsistent, and even contradictory (cf. Tversky, 1993). Nevertheless, humans perform surprisingly well when solving spatial problems like route planning and wayfinding in familiar environments. On that account much scientific research efforts were put into investigations on how humans learn, structure, and reason about familiar and partially unfamiliar spatial environments in order to obtain the main aspects of spatial information that are utilized for spatial problem solving tasks.

Structural aspects of spatial environments

The pioneering work of Lynch (1960) describes how the citizens of three different American cities structure the information about their urban environment, i.e., the mental images of their cities. Lynch defines the main structural elements that result from his various exploration studies as *landmarks*, *nodes*, *paths*, *edges,* and *districts*. *Landmarks* are salient features of the urban environment like buildings and places. They serve the observer as reference points. *Paths* are streets or lanes. *Nodes* are path intersections, bridges, or changes of transportation modes and form important points. *Edges* are boundaries of areas, which form a physical barrier (e.g., rivers, highways from a pedestrian point of view). *Districts* are areas in a city that share a common property (e.g., shopping areas, residential areas). Lynch describes that individuals tend to use global landmarks in new environments for the purpose of orientation. Gradually, the individuals add further information to their knowledge until a cognitive map is constructed.

Consequently, mental representations consist primarily of topological knowledge, i.e., how the landmarks are interrelated. Depending on the medium used for acquiring knowledge about the environment such topological representations can be gradually mapped to survey knowledge, allowing for adding new spatial relations to cognitive maps.

Human spatial problem solving strategies

When solving spatial problems, humans operate on hierarchical knowledge representations stored in long-term memory. Stevens and Coupe (1978) demonstrated the hierarchical organization of mental geographic knowledge using a spatial problem, i.e., asking students of a Californian university about relative positions of two American cities, Reno and San Diego. The results of the experiment have shown that the subjects derived the spatial relations between two cities from the super-ordinate spatial relations between the states of California and Nevada when solving this problem. To obtain the missing knowledge about the relations between the two cities, subjects utilized the containment relations of the cities to the corresponding states, which resulted in most of the cases in a false answer, i.e., Reno being further east than San Diego, albeit it is further west (see figure 1).

Fig. 1. Map of California and Nevada exhibiting the relative positions of the cities of San Diego and Reno

Hierarchies in human mind are used for categorization of information and particularly for structuring large-scale environments into regions. Regions "*help people organize their understandings of the world in an efficient manner, they also help various activities in space occur more efficiently*" (Montello, 2003).

The principle of *regionalization* of large-scale environments provides a basis for series of navigation experiments conducted in a virtual reality lab (Wiener, 2004). The results of the experiments have shown that regionalization facilitates spatial problem solving tasks like navigation in unfamiliar large-scale environments. Mental representations formed in regionalized environments contain super-ordinate connectivity relations, i.e., *region connectivity*, which allow for performing navigation tasks more efficiently.

Hierarchies in Artificial Spatial Systems

"*In order to effectively manage complex environments the spatial system must be capable of discarding useless information and breaking large environments into collections of smaller environments*" (Chown, 2000). Therefore, a significant body of research is concerned with development of spatial systems which operate on hierarchically organized spatial knowledge representations (e.g., Chown, 2000; Kuipers, 2000; Leiser & Zilberschatz, 1989).

Mental representations contain primarily topological information which describes how different locations are interconnected. This outstanding property of mental representations was successfully applied in various artificial spatial systems, making their orientation and route planning performance more robust. For example, the topological level of Kuipers' Spatial Semantic Hierarchy (2000) consists of the features of external environment, defined by places, paths, regions and their connectivity, order, and containment relations. Also the spatial system PLAN by Chown (2000) operates on topological representations which consist of a network of topologically interrelated landmarks and a network of gateways. The gateways mark the transitions between different regions of space.

Spatial systems have to be capable of structuring the spatial knowledge into regions and be able to distinguish between the paths which connect places from those connecting regions. Although hierarchical route planning algorithms provide sub-optimal solutions, they require less computational power and are more efficient.

Regionalize and Conquer

In the following, we are going to introduce a representation of the spatio-temporal problem domain which utilizes the demonstrated properties and aspects of hierarchical spatial knowledge representations in artificial systems as well as in human mind.

To establish an adequate dialog between a human and an assistance system we have to structure the problem domain into regions. Operations on hierarchical region-based structures resemble human hierarchical spatial reasoning strategies (Hirtle & Jonides, 1985; Stevens & Coupe, 1978). Furthermore, *"regionalization has its definite analytic and communicative utility. It simplifies complexity and avoids unnecessary precision, both in thought and speech*" (Montello, 2003). Consequently, the proposed spatial representation consists of *locations*, *regions*, *nodes,* and *paths*.

Locations are points of interest, where one or more types of activity can take place. A location is an abstract one-dimensional point. To communicate a location to a user, each location has a name. The name has to be unique within an activity region that contains the location. Locations can also serve as an abstraction of a region.

An *activity region* contains one or more spatially proximate locations and a connectivity node. The locations within an activity region share specific properties according to the type activities, which are supposed to be pursued in that region.

A *connectivity node* is a location, which connects a set of locations within an activity region (see figure 2). Such node has a connectivity cost, which results from a connectivity measure, e.g., an average distance cost to the corresponding locations.

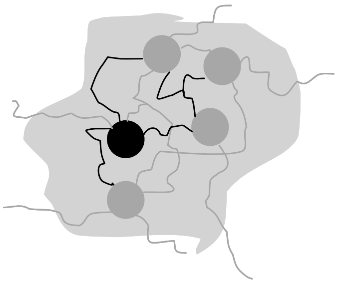

Fig. 2. A node stands for connectivity costs of the locations within a region

Super-ordinate regions structure an unfamiliar environment and contain activity regions. The structuring criteria encompass properties of the environment which are relevant for the current spatio-temporal planning task. For example, when planning an individual journey administrative regions, e.g., federal states together with topography can be considered as relevant. The containment relation is represented by a *part-of* relation between super-ordinate und activity regions.

The proposed representation structure consists of a hierarchy of locations, activity regions and super-ordinate regions, related to each other by *part-of* relations. Such partonomies allow for representing and reasoning about qualitative topological relations between regions with rough boundaries (Bittner & Stell, 2002). The connectivity nodes assigned to activity regions are linked with each other via paths. Paths consist from nodes and edges and carry the distance costs.

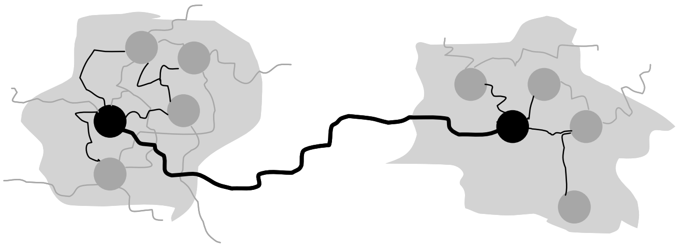

Fig. 3. Nodes connect regions

Figure 3 illustrates different locations within a region. One of the locations represents a connectivity node that binds other locations. Such node can be one of the locations of interest, or another alternative location that binds the locations within a region with a better connectivity cost.

The proposed hierarchical region-based representation is built in a bottom-up manner. The following section describes how the proposed region-based hierarchy allows for solving spatio-temporal planning problems efficiently in an interactive way.

Region-based assistance with spatio-temporal planning

It is assumed that the required information about the locations of interests and paths between them can be provided to the assistance system by a geographic information system (GIS). The assistance system first generates the corresponding activity regions that contain several locations of interest of the required activity type.
Figure 5 shows an abstract depiction of a hierarchically organized region-based representation. The locations of interest are bound into activity regions associated with the activity types: “hiking”, “swimming” and “sightseeing”. The locations inside the activity regions are bound to the corresponding connectivity nodes: *node 1a, node 2a, node 3a, node 4a, node 5a,* and *node 1b, node 2b, node 3b, node 4b*, respectively. Each of these connectivity nodes represents a connectivity cost for the corresponding activity type within an activity region. *Region A* and *Region B* contain the sets of regions {*1a, ...,5a*}, {*1b,...,4b*}.

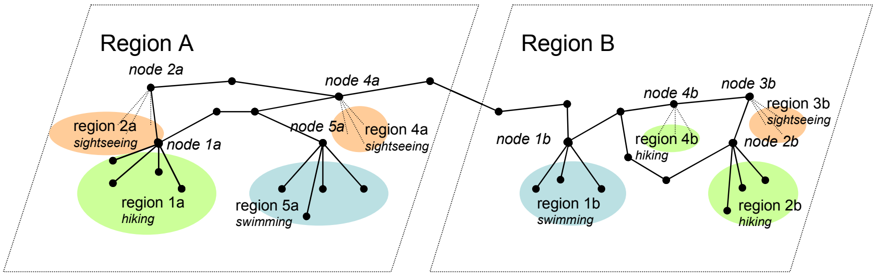

Fig. 5. Region-based representation

In order to obtain all feasible spatio-temporal configurations all permutations in the order of the activities in the given spatio-temporal configuration $Conf = (a_0, a_2, \ldots, a_i)$ and all possible assignments of the corresponding regions, e.g., *1a, 2a, 3a* etc. have to be taken into consideration. However, a significant part of the problem space can be pruned when using partial orders of the super-ordinate regions *{Region A, Region B}* or *{Region A, Region B}.*

A user guides the search process by definition of additional constraints, e.g., selection of partial orders of super-ordinate regions, or partial orders in the given set of activities. The proposed representation allows on the one hand for specification, on the other hand for relaxation of constraints at different levels of the spatial region-based hierarchy. Furthermore, assistance with pre-visiting of unfamiliar environments can be provided at different levels of granularity with no requirement on precise assignments of particular locations, which can be refined at a later point of a journey. In this vein, the assistance system accompanies the problem solving process, resembling human hierarchical reasoning strategies about spatial relations. It provides a possibility to define partial orders on a coarse level and to step into the detailed level to find feasible partially refined spatio-temporal configurations keeping the global solution space consistent.

Outlook and Future Work

The introduced hierarchically organized region-based representation allows for assignment of spatial constraints and definition of partial orders of regions and activities at different levels of granularity. The proposed assistance system operates on hierarchically organized locations, activity regions and super-ordinate regions. For the purpose of the simplicity of the illustrated example, an adequate mapping procedure of activity regions to commonly used administrative regions has not yet been considered. Since activity regions may contain locations of different activity types, they may overlap with more than one administrative region. In order to deal with such cases structuring criteria based on qualitative spatial relations between activity regions and administrative regions have to be considered. However, this is one of the topics of future work.

Another important topic is the establishing of an adequate interaction model between an assistance system and a user. Skillful navigation operations for observation of the solution space have to be defined. Such operations serve for representation and manipulation of the spatio-temporal configurations, like, e.g., the demonstrated specification of partial orders at different levels of the region-based hierarchy. For this purpose human problem solving strategies (cf. Newell, & Simon, 1972) and reasoning with mental models (cf., Johnson-Laird, 1983), particularly preferred mental models (cf. Knauff et. al., 1995) can be utilized. These topics are also a matter of further research.

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