On modeling of large-scale environments for solving spatio-temporal planning problems

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Abstract: the paper introduces a cognitively motivated approach for structuring and representing of unfamiliar large-scale environments. The proposed region-based representation facilitates collaborative spatio-temporal planning, where problem solving process is shared between a user and an assistance system. The problem domain is structured hierarchically into regions resembling human decision space. The region-based structure makes it possible to specify spatial constraints as well as to generate alternative solutions at different levels of granularity.

Motivation

Finding a path from A to B in a network consisting of nodes and edges is one of the classical problems in the history of computer science. One of the most famous shortest-path algorithms has been introduced by Dijkstra in 1959 (Dijkstra, 1959). Yet, several decades of interdisciplinary research in spatial cognition has been needed to develop the cognitively motivated principles for communication of route instructions, which help people to find a way from location A to location B in common street networks (e.g., Denis, 1997; Tversky & Lee, 1999; Dale et. al., 2002).

Psychological investigations on how humans perceive, learn and structure their knowledge about familiar or unfamiliar environments, and correspondingly how they perform spatial problem solving tasks, provide theoretical background for development of cognitively motivated models for representing and communicating knowledge about spatial environments (e.g., Rüetschi & Timpf, 2005). Spatial assistance systems (e.g., Rehrl et. al., 2005), which operate on such models contribute to user-friendly assistance with navigation tasks as well as a seamless transition from indoor to outdoor environments.

Availably of additional meta-information about geographic regions and locations makes it possible to associate specific properties, such as points of interest (e.g., national parks, museums or sightseeing attractions) with the topological data, i.e., how locations are connected with each other. Such information provides a basis for assistance with further spatial problems like spatio-temporal planning. A typical example of such task is planning of an individual journey or a city tour.

When planning a journey through an unfamiliar environment, travelers have to make a decision on *what* they are going to do, i.e., specify a set of activities. Along with the question *what*, they have to decide *where* the activities take place. Since the most of the interesting places and attractions are distributed around a country or a city, the corresponding locations have to be grouped together, to reduce the time for traveling from one place to another. Furthermore, journeys are usually constrained in time, so that journey planners have to fix the durations of their activities and put them into a feasible temporal order. Yet, especially in the early planning stage the information on *what*, *when* and *where* is known only partially and is available at different levels of granularity.

The next section outlines the characteristics of the problem domain from the human problem solving and knowledge representation point of view. The subsequent section identifies the gap between the existing approaches: task-orientated map production and personalized tour generation. To fill the gap, a *collaborative assistance* approach with spatio-temporal planning is introduced. Since collaborative assistance requires user's active participation in the problem solving task, human cognitive capacity and mental processing of geographic information has to be taken into consideration. The paper describes a cognitively motivated approach for structuring of the spatio-temporal problem domain, which allows for an adequate dialogue between a human and an artificial assistance system during collaborative spatio-temporal planning tasks.

Characteristics of spatio-temporal planning

Spatio-temporal planning encompasses putting a set of activities into a feasible order under consideration of spatial and temporal constraints. The corresponding constraints can be formalized as a set of activities with the following attributes. Each activity has an activity type (*what* to do), duration (*how long*), temporal order (*when*), and a spatial assignment (*where*).

Psychological findings describe mental knowledge representations as hierarchically organized and consisting of loosely coupled, contradictory and nested knowledge fragments (e.g., Tversky, 1993). Consequently, even if a journey planner has a rough idea of the activity types he/she prefers, the initial spatial assignments are known at different levels of granularity, e.g., a particular country, a part of a country, a city, etc. Various information artifacts like maps, traveling guides and the Internet provide users with information about different locations, which may sound interesting, but travelers have no idea of activities they can pursue there, i.e., type of activities that can be performed in a particular location or a region.

Although journeys and activities are constrained in time, optimization criteria regarding an overall goal of a journey have to satisfy such important criteria, like personal preferences, moods or even emotions, which are in turn hard to acquire and to formalize. Furthermore, journey plans are specified only to a certain degree, in order to be updated or changed in the course of traveling. Since the initial problem solving state encompasses only rough spatial assignments and optimization function together with a particular goal state are not well-defined, planning an individual journey through a foreign country is an ill-structured problem (Simon, 1973).

Existing approaches for assistance with similar types of problems

The existing approaches for assistance with the similar spatial problems found in the literature can be divided into two categories: task-oriented map production and personalized tour generation.

Task-orientated maps

Task-oriented map production (Zipf & von Hunolstein, 2003) aims at representing the relevant aspects of the environment, which are required for solving a particular spatial problem, providing users with answers to the questions, e.g., “where I am?” - you are here maps (Richter & Klippel, 2002), “what can I do next?” - adaptive mobile maps (Reichenbacher, 2005), “how can I get from A to B?”, - route directions (e.g., Richter & Klippel, 2005). Such representations 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 (Freksa & Barkowsky, 1996).

Yet, the exemplified problem solving tasks, which can be assisted using task-oriented map production, either encompass relatively small areas situated in user’s vicinity, or are well-defined, like, e.g., route instructions from A to B. And finally, the reasoning part about the combination of spatial and temporal constraints has to be performed mentally.

Tour generation

Another approach to assist in problems like journey planning is a personalized tour generation. In order to reduce the number of possible destinations, which come into consideration, such systems utilize user modeling and personalization techniques. For example, the profiling data including user’s preferences allows for reducing the number of the proposed items delivered by search engines (Schmidt-Belz, et. al., 2003).

A similar approach introduced in (McGinty & Smith, 2002) utilizes user modeling and profiling data in order to generate personalized routes between predefined starting and goal destinations.

The main disadvantage of the tour generation approach is the exclusion of user’s active participation in a process of planning. In doing so, the generated tours are difficult or even impossible to change. Personalization takes into consideration preferences of a single user. However, traveling is a social venture and no one likes to travel alone. Consequently, the profiling data has to be shared among the people, who travel together. However, it is not conform to the term “*personalization*”.

From that follows, that the spatio-temporal planning cannot be totally outsourced to a computational constraint solver or a search engine, but requires collaborative search for a solution.

Collaborative assistance systems

Collaborative assistance systems accompany problem solving process rather than providing users with a single solution (Schlieder & Hagen, 2000). A collaborative assistance system generates a set of alternative solutions which fulfill specified formalized hard constraints, for example, duration of the whole journey and durations of each activity, together with partially specified activity types and spatial assignments. The generated solutions have to be observed by a user, who decides, whether the generated solution space is “good enough” for a current situation, or should be refined due to personal preferences. In the second case, a user can specify further constraints, or on the other hand change or relax existing constraints in order to obtain improved solutions. In doing so, the constraint satisfaction processes is shared between an assistance system and a person. However, to establish an adequate dialogue between a user and an assistance system, the structure of the spatio-temporal problem domain has to resemble the human decision space.

In our recent works (Seifert, et. al., to appear) we introduced a concept of a cognitively motivated representation structure, which allows for specification of constraints as well as generation of alternative solutions at different levels of granularity. In the following, the paper provides a refined overview about the proposed region-based representation structure.

Region-based representation

The region-based representation is based on psychological findings considering human processing of geographic information, i.e., cognitive maps (Hirtle & Heidorn, 1993), cognitive atlases (Hirtle, 1998) and cognitive collages (Tversky, 1993). To facilitate the human co-processing of geographic information during the collaborative problem solving the system utilizes the cognitive phenomena *regionalization* (Montello, 2003) and *region connectivity* (Wiener, 2004).

Regionalization

“*Regionalization has its definite analytic and communicative utility. It simplifies complexity and avoids unnecessary precision, both in thought and speech*” (Montello, 2003). Therefore, the proposed region-based representation structure consists of hierarchically organized regions.

The geographic information provided by maps and geographic information systems (GIS) is extremely rich. Modern GI-Systems are capable of representing and manipulating of spatial and topological information about administrative, topographic, as well as thematic regions. However, to reduce the representational complexity and to convey the structure of an unfamiliar large-scale geographic environments popular traveler guides like the “Traveling Guide of California” (Vis a Vis, 2004), combine the administrative regions into *super-ordinate* parts of a large-scale environment (see Figure 1).

Figure 1: Example partitioning of California, USA[1]

Such global parts divide a large-scale geographic area into a relatively small number of regions. If such parts cannot be mapped to administrative regions, they are usually labeled by geographical or climatic specifics of the environment in combination with cardinal directions, like North Coast, Central Cost, South Coast, etc. (cf., Lyi Y. et al., 2005).

The proposed assistance system operates on a spatial hierarchy, which spans three conceptual layers: *locations*, activity type specific regions, denoted as *activity regions* and *super-ordinate* regions. *Activity regions* represent sets of *locations* which share some particular property or facility, (e.g., possibility for hiking, water sports, etc.). The size of *activity regions* depends on the scale of the environment in which a journey is planned, and of course on the duration of the whole journey and the durations and the corresponding activities. For example, an *activity region* which encompasses a visit to several museums in Rome during a weekend is smaller than an *activity region* of skiing in the Alps for a week. *Locations* bound into *activity regions* are situated at the lowest level of the spatial region-based hierarchy.

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[1] The example partitioning is produced from the test data acquired from different information resources.

Region connectivity

Series of psychological experiments conducted in a virtual reality lab have shown that regionalization facilitates spatial problem solving tasks like navigation in partially familiar large-scale environments (Wiener, 2004). Mental representations formed in regionalized environments contain super-ordinate connectivity relations, i.e., *region connectivity*, which allow for performing spatial problem solving tasks like route planning more efficiently.

The proposed region-based spatial representation structure consists of **locations**, **regions**, **nodes**, and **paths**.

Locations are points of interest, where *activities* with specific *activity types* can take place. To communicate a *location* to a user, each *location* must have a name. The name has to be unique within an *activity region* that contains the *location*. A *location* can also serve as an abstraction of a region.

Activity regions contain one or more *locations* and a *node*. Such *node* is related to a *location* which connects a set of *locations* sharing the same activity type, e.g. visiting a set of museums, within an *activity region*. Such *node* has a connectivity cost, which results from an approximation, e.g., an average distance cost to the corresponding *locations* (see Figure 2). For the purpose of communication, an *activity region* has a unique name within a *super-ordinate region*. If no direct mapping to an administrative region is possible, such name is constructed from the corresponding super ordinate region and cardinal directions, i.e., (in the North, South of, etc).

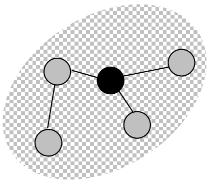

Figure 2: Locations within an activity region connected by a node.

Super-ordinate regions of an unfamiliar large-scale environment contain *activity regions*. The containment relation between the regions is represented as a *part of* relation. Such region-based partonomies allow for representing and reasoning about qualitative topological relations between regions with rough boundaries (Bittner & Stell, 2002). Furthermore, the proposed representation structure includes *neighborhood relations* holding between super-ordinate regions.

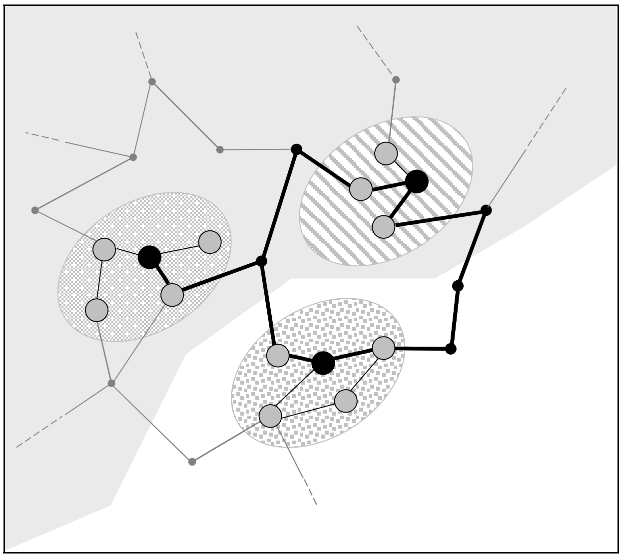

Figure 3: Connectivity of activity regions

A **node** with a connectivity cost is related a *location*, which binds the *locations* within an *activity region*, and is connected with other *activity regions* via *paths* (see Figure 2). The Figure 2 illustrates three *activity regions* situated in two different *super-ordinate regions*.

Paths connect different *activity regions* via *nodes* and have *distance costs*. Each intersection of path segments is also modeled as a *node*, which is related to some *location* but carries no additional connectivity costs.

Solving spatio-temporal problems interactively

Using regions and the relations between them, the initial problem solving state can be specified as a list of activities, in the form of the following data structure (see Figure 4).

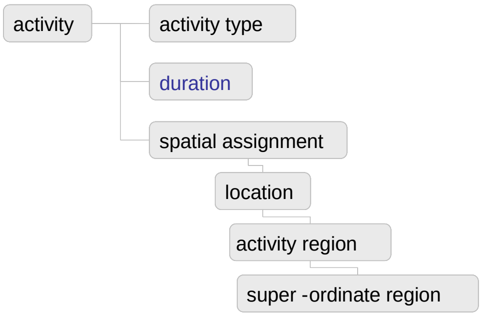

Figure 4: Activity structure.

The definition of duration of each activity is mandatory, whereas activity type and spatial assignment are optional. Using the region-based representation structure the spatial assignments can be specified at different levels of the spatial hierarchy, e.g., as a location, specific activity region, or a super-ordinate region. The temporal constraints can be expressed as valid temporal order of activities, i.e., following one after another.

Allowing user to specify particular activity regions, or a particular order in which the super-ordinate regions are going to be visited interactively, prunes significant parts of the problem space. Using the cognitive phenomena of regionalization and region connectivity, the proposed representation structure facilitates the generation of alternative solutions and allows for an adequate dialog between a human and an assistance system.

Outlook and future work

The proposed representation structure is based on the assumption that humans operate on mental representations of spatial environments consisting from regions. Series of psychological experiments provide evidence, that such regions are hierarchically organized (e.g., Tversky, 1993; Hirtle & Heidorn, 1993; Hirtle, 1998) and connected with each other (Wiener, 2004). The described representation structure consists of *locations*, *activity regions*, *super-ordinate regions*, *nodes* and *paths*. The size of *locations*, *activity regions* as well as *super-ordinate regions* depends on the spatio-temporal context of the journey: durations of each activity, duration of the whole journey, and on the velocity of user’s locomotion. The paper exemplifies three layers of a spatial hierarchy: *locations*, *activity regions* and *super-ordinate regions*. However, conceptual hierarchy of the corresponding *activity types* (e.g., swimming is a sub activity type of water sports), allows for introducing further levels of granularity to the spatial region-based hierarchy.

Since there are only several means of transportation, which can be used for traveling today, the way people perceive, learn and structure large-scale environments supposed not to be continuous, but discrete. To identify the cognitively adequate granularity levels of activity regions together with suited activity types, more empirical research should be focused on task specific mental representations of large-scale environments.

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