Assistance for Spatio-Temporal Planning in Ubiquitous Computing Environments Based on Mental Models

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Abstract
This paper addresses a spatio-temporal configuration problem that consists of integrating a set of interdependent constraints. The problem's scenario is set to a day at a trade fair during which meetings need be dynamically scheduled and assigned respective spatial locations on a map. For this type of configuration problem, mental problem solving is model-based, i.e. the problem is mentally solved by instantiation of constraints; where multiple instantiations are possible, typically only few get constructed. As a result, the performance of a corresponding planning assistance system does not only depend on its use of computational resources but also on the user's cognitive effort required to understand the current state of the system and to guide the planning process. Corollary, cognitive processing models have to be integrated into the assistance system to allow for better predicting current cognitive efforts and reasoning preferences. We analyze the scenario with respect to model-based problem solving strategies and propose first ideas towards an assistance system that presents itself through different media in a ubiquitous computing environment.

Keywords
Cognitive assistance, spatio-temporal reasoning, mental models, ubiquitous computing.

1 INTRODUCTION
The problem type addressed in this paper is the integration of a set of interdependent spatial and temporal constraints that make up a configuration problem. Typically, the problem is dynamic as either the set of relevant constraints may vary during the problem solving process, or variation may exist in the set of values that are considered legal assignments for a specific variable. The constraints are usually interdependent to some degree, such that the selection of an assignment to one variable may restrict the set of legal assignments for another. The scenario of a sample configuration problem of this type, namely the dynamic planning and scheduling that takes place during a day at a trade fair, will be described in detail in the following section.

In many cases, not all constraints of a problem are amenable to formalization, resulting in partially unformalized constraint problems (cf. [20]). With problems of this class, a number of decisions cannot be outsourced to an automatic constraint solver for various causes, and the human problem solver and a computational assistance system must collaborate in the problem solving process. In doing so they constitute a interactive reasoning system. Reasons why constraints may not be automatically treated include that they relate to a human's implicit preferences or knowledge, to emotions, to issues that involve esthetics, or, simply, that they are hard to verbalize (cf. [3]).

Clearly, the performance of an interactive human-computer reasoning system does not only depend on the use of computational resources in the computational part but also on that of human cognitive resources. Take as an example the user's cognitive effort that is required to understand the current state of the assistance system, or the effort required to guide the planning process (e.g. by selecting partial solutions that were generated computationally). Human intelligence is one of the bottlenecks in the process; in order to get good collaboration and to allow for better predicting current cognitive stresses in the human reasoner cognitive processing models are required within the computational part.

In the following section, we will further consider the trade fair scenario. Afterwards, we will turn to mental model-based problem solving in Section 3. Consequently, requirements will be assessed for assisting mental model-based reasoning. In Section 5, we will present the outline of an assistance system that operates through different media in a ubiquitous computing environment.

2 SCENARIO: A DAY AT A TRADE FAIR
Imagine that you are attending a trade fair where you intend to visit a number of exhibition booths and where you want to talk to a number of people. You have compiled a list of events in which you want to participate, as well as a checklist of meetings that you would like to arrange. Now, you are in the middle of the trade fair, you hold a leaflet with the spatial overview of the trade fair area in your hand, and you are about to decide how to manage your agenda to get everything done within the time available.

So, maybe you are about to decide between two options: one is to go to the northern part of the fair and watch the new technologies at a specific manufacturer's exhibition that you planned to visit. It would take about 10 to 15 minutes to get there, and probably you could get a cup of coffee and a piece of cake there. The second option is to prepare to go to a scheduled appointment with a customer in the west side of the fair. This appointment will start in one hour from now, and it will take 20 minutes to get to the customer's booth. Actually, you will have plenty of time if you choose option two. Suddenly, your mobile phone rings. A colleague of yours informs you of a very interesting booth in the eastern part of the fair. You know that it would take about 10 minutes to get to the booth advised by your colleague and maybe 30 minutes to take a look at the exhibition and to chat with your colleague about the things presented. On the other hand, it is almost lunch time and a snack would be nice. So how do you decide right now and what are the consequences for the other events that are on your list?

If you were able to follow the description up to this point, you have good working memory capacity. But don't you think a visualization of the situation not only in your mind, but also in your hand is a good support in such a decision process? So far, the aspects mentioned have been more or less static. That means that new events may be added to the list of things to be dealt with, but the locations at which events will take place are fixed.

The entire problem becomes more complicated if you think of making an appointment with a person, who is also moving through the trade fair. In this case, the place where you may meet the other person is not crucial, but the time and place of the appointment must fulfill certain constraints which are given by the fact that the respective partners are moving around. Clearly, the meeting must take place at a point where the two persons' routes through the spatio-temporal environment cross each other. To achieve this goal, the information exchange about the persons' tentative locations during the day at the trade fair becomes a part of our problem.

We have to deal with the following questions:

- What is the informational structure of the type of problems described above that must be handled by the assistance system?
- What kinds of mental processes are involved in solving spatio-temporal configuration tasks of the type outlined above?
- What kinds of cognitive restrictions have to be dealt with?
- How can restrictions of human working memory be overcome by a cognitive assistance system?
- Which technical devices can be used for the interaction with the assistance system?

The demonstrated trade fair environment has a well defined spatio-temporal structure together with a set of corresponding constraints. However, not only the spatial and temporal constraints contribute to the complexity of the mental spatio-temporal configuration task; moreover, there are also the following categories of variables that influence the mental task to be performed:

People. Often there exist preferences for meeting people (i.e. a partial order), specifying whom you want to meet first (or in any case), and who can be met at a later point in time.

Time and personal preferences. For example, you may want to arrange an important appointment in the morning or at the end of your day at the trade fair.

Place. The place of an appointment may also be chosen according to temporal and spatial constraints. For example, if you cannot find the time to meet a particular person during the fair you may want to propose to convene in the evening for dinner.

The mental representations constructed by the trade fair visitor include instances of variables that have to be mentally rearranged according to the given situation. Obviously, there may exist more than one spatio-temporal configuration that satisfies a given set of constraints. The following section describes mental decision making processes in more detail and helps identify the requirements of the assistance tasks.

3 SOLVING THE PROBLEM MENTALLY

We will now have a look at the peculiarities associated with solving the presented type of problem mentally: where the problem's complexity is sufficiently high, mental problem solving can be expected to rely on the construction of mental models and on reasoning with them (cf. [11]). Factors that influence problem complexity are, for instance, the number of relevant constraints and the degrees of variable interdependency. Mental models allude to the term model such as used in formal model theory: they provide a semantics and instantiates a set of constraints. It is important to note that even where the construction of many models is theoretically possible, only few get constructed in mental problem solving. Usually, the mental mechanisms involved are thus quite different from the mechanisms employed by standard constraint solvers, and planning assistance systems have to take these differences into account.

With respect to our trade fair scenario, we identify various types of knowledge that have been investigated in spatial cognition: to begin with, the list of appointments that need to be scheduled represents a (largely 1-dimensional) ordering on information, which is typically processed based on mental models (e.g. [12]). The trade fair plan conveys a (largely 2-dimensional) spatial overview of the general area to be visited; its mental correspondences have been described by metaphors such as cognitive maps, cognitive collages, atlases, or spatial mental models, depending on the field of research and the focus taken (e.g. [22], [10]).

In the scenario, both types of information must be integrated with respect to the amount of time that our protagonist has available, given how long individual activities such as meetings take, and given the time required to get from one location to another. The temporal structure of the problem can be described as an ordering structure on time intervals related to events (cf. [1]).

For our fair trade scenario, the use of mental models implies that the visitor will not search the entire problem space for all possible solutions to his scheduling needs and then determine which one of these to put into action; rather, his mental problem solving resembles a depth-first search with some (maybe non-systematic) backtracking and a preference to accept one of the first models encountered that fulfill the constraints to a tolerable degree. Determining the order in which constraints are instantiated in the model is therefore crucial to the problem solving as it determines the subspace of the entire problem space that is searched. The actual order can be due to specific preferences, to the reasoner's experience with solving problems of the type under consideration, as well as to the structure of the current problem. It is these factors that determine which of all possible models will be constructed.

However, not all constraints need necessarily be integrated into a single model. Rather, the problem may be split into partial problems whose solutions are integrated later on, depending on the high-level strategies chosen (cf. the human problem solving approach taken in [18], and the range of variations proposed since, e.g. in [2]).

Since the most constraining structure in the problem is a spatial one (the fair trade area to be navigated in), and since the integration of all knowledge aspects (space, time, ordering of events) is sufficiently complex, it can be assumed that the mental representation will be in the form of mental images [5]). Mental images are a specific form of mental models that integrate spatial knowledge into a spatio-analogical representation format. This format exhibits a number of visual properties; in fact, the mental representation structure for mental images, the visual buffer, is based on neural structures that are also used in real vision processes (i.e., visual object or scene recognition, cf. [14]).

Whatever the actual high-level problem solving strategy may be, human mental reasoning is restricted in the amount of available attention and storage capacities. The fact that mental reasoning is based on the construction of specific models rather than of all models can be interpreted as an adaptation to these restrictions. Another principle towards an economic use of resources is outsourcing: mental representations are off-loaded to the environment and analogies between mental and external representation structures are exploited to assist mental reasoning processes (cf. [24]). Writing a shopping list is a good example of creating an external representation that is meant to assist internal representations, making sketches and scribbles while mental reasoning is yet another.

4 ANALYSIS OF ASSISTANCE TASKS

We will now identify a number of basic requirements for assisting the mental solving of our trade fair problem. The first one addresses capacities of mental processing and draws on the observation that, typically, visual mental images as a specific, integrated type of mental representation are constructed whenever a sufficiently large number of knowledge fragments are involved. Mental images instantiate a set of constraints in a quasi-pictorial manner. Along with an increase in specificity that necessarily goes along with the instantiation process (i.e. through graphical constraining, [19]), it is the specific representational format that allows to read off novel bits of information. In this property, mental images exhibit many similarities to external diagrams: they offer free rides in reasoning [21], they group information that is needed at the same time, and they establish correspondences between knowledge fragments without the need to introduce labels [17].

Much has been written on the specific role that external diagrams, sketches, pictures, and graphs play for carrying out a variety of cognitive tasks: they may, for example, reduce the number of choices that a reasoner has to take while reasoning or they may help him employ the spatial dynamics in the environment (external computation, cf. [13]). Mental images and external diagrams contribute to a dialectics between a reasoner's inner processes and the external world [7],[8], in which mental constructions are externalized, internalized again, externalized, and so on. Generally, this close relation between mental images and external diagrams is attributed to a close coupling of imagery and visual perception (e.g. [6]; [15]).

Limitations in storage and attentional capacities are inherent to mental reasoning processes. External representations do not have comparable storage restrictions; this is why we often take notes during mental reasoning. Where mental problem solving involves the construction of mental images, external diagrams possess specific representational qualities and should be employed as for the assistive setting. Additionally, in cooperative assistance, external representations play a triple role, as they may be used as external notes for mental reasoning, or serve to convey information from the human reasoner to the assistance system and vice versa.

The second requirement which we can identify for assisting a mental solving of the trade fair problem is derived from the observation that mental problem solving is model-based, and that even where the construction of many models is theoretically possible, only few get constructed. The selection of those few is not arbitrary, rather there exist preferences in mental model construction [12]. To provide an adequate context, the assistance system needs to keep track of the (set of) model(s) currently constructed by the user. Here, interaction paradigms are needed of how actions are reflective of changes in mental states. With respect to the assistance provided, two general modes are conceivable: in-line assistance, where the models proposed by the computational system are similar to those mentally constructed by the human reasoner, and complementary assistance, where the system provides a number of alternative models.

Figure 1 demonstrates two different alternatives of the trade fair visit as displayed on a PDA. The scheduled appointments take place in halls H6, H10, H13 and H1. Visits to the booths in halls H5 and H7 are not fixed in time. The diagram on the display is a visualization of a mental image modeled by the assistance system. Therefore, only the halls which are important for the decision process are shown. The appointments are annotated to halls; routes are schematically denoted by map gestures (represented by arrows). The corresponding details to the appointments are listed under the diagram. The assistance system highlights the differences (e.g. H5 and H7) between the two alternative solutions. By clicking on the diagram area the assistance system provides additional information according to the spatial context of the selection (e.g. top display: café near H6, bottom display: restaurant near H10).

Cognitively, the trade fair problem is especially demanding as the spatial and temporal constraints involved are not stable over time. That is, the set of relevant constraints may vary during the problem solving process, or the variation may be in the set of values that constitutes the legal assignments for a specific variable. It is important that the system mediates the dynamics to the user so that only changes in currently relevant parts of the problem are communicated (see marked differences (highlighted color) between the alternatives H5 and H7 in Fig. 1).

A second form of dynamics lies in how the human problem solver approaches the decision space of the trade fair problem: Typically, not all possible problem states will be considered and, commonly, at a given moment and a given place, not all possible candidates for the next decision will be taken into account. The selection of the actual subspace of the decision space that will be considered for the planning process is highly context-dependent; as a result, a varying extent of the subspace that gets considered introduces further dynamics (cf. [2]).

As a result, an assistance system needs to carefully select the information that it passes on to the human planner, and it needs to tune it depending on the user's actual location in time and space. The planning context needs to be maintained while the user moves in space and while time goes on. On the other hand, the assistance needs to keep track of model changes (i.e., when the human planner decides to momentarily consider appointments later in the day, or when he rearranges the current schedule). The user's current spatio-temporal context provides some indication as to which parts of the decision space form part of the actual mental model, and which do probably not. It is this requirement to carry on with planning and interaction tasks while changing spatial and temporal locations that requires a ubiquitous computing infrastructure.

5 OUTLINE OF A MODEL-BASED ASSISTANCE SYSTEM

As described above, the mental model-based assistance system supports our user in highly dynamic spatio-temporal situations. However, we have to define media that support the user in the spatio-temporal environment. The following requirements should be satisfied:

User mobility. The assistance system should provide user mobility [3].

Capability to visualize mental images. During the assistance tasks the user's mental model (i.e. in-line assistance) and related alternatives (i.e. complementary assistance) should be visualized.

Awareness of changes. The user should be informed of changes in the appointment schedule and be able to perform changes himself.

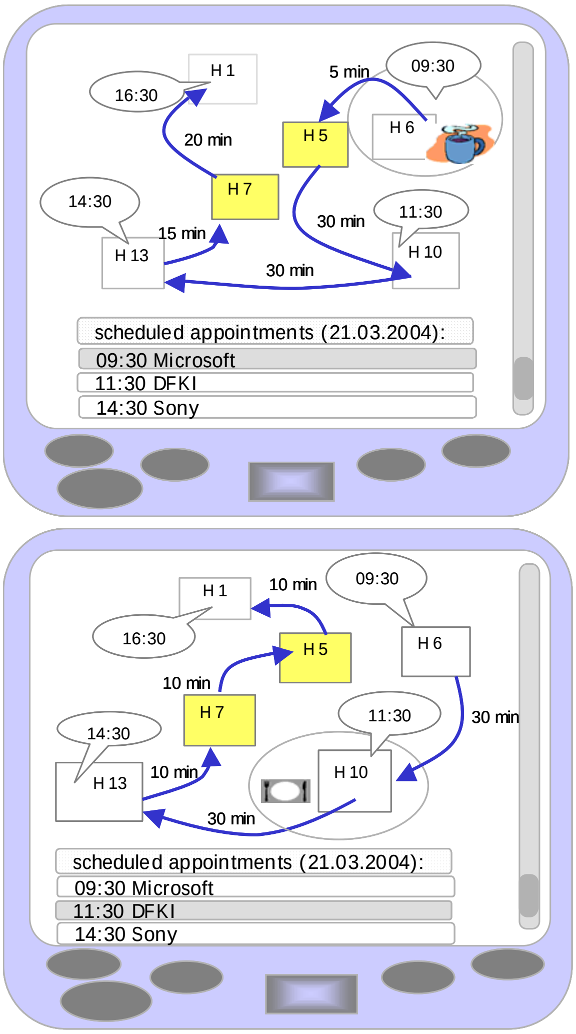

Figure 1. External representation of two alternative mental images.

Nowadays, there exist a great variety of sophisticated communication and desktop devices. From the described requirements it follows that on the one hand we need a mobile communication device and on the other a device that is capable of visualization and interaction with mental images (i.e. externalization and internalization of diagrams). A device that satisfies all of the requirements is a PDA. However, PDAs only provide a poor ability to interact with diagrams. The best solution for interactions with mental images are devices like smart boards.

In the following, we will discuss how the combination of the two device types operates in a ubiquitous computing environment. Subsequently, different communication scenarios (e.g. multi-user multi-device communication) will be discussed.

5.1 Multi-User and Multi-Device Communication

The ubiquitous computing domain proposed here employs wearable PDAs and stationary smart boards. Both types of devices are network enabled. The protocols responsible for the secure transfer of appointments and preferences are integral parts of the assistance system. The smart boards in the proposed setting are used by many anonymous users. Fundamental issues of designing multi-user multi-device interfaces were discussed in [16]. Among others, management, technical, and social issues and the level of trust between the users must be taken into account to avoid confusing situations. Different approaches with respect to secure data access are discussed in [9].

It is assumed that the users can transfer their personal schedules from the PDAs to the smart boards and vice versa. For the sake of giving a simple communication scenario within this paper, the examples are reduced to two communication partners. Nevertheless, also scenarios with more than two users are needed for practical application. According to the technical prerequisites described above the following communication scenarios can be considered:

Two mobile users with PDAs. To arrange a meeting, users have to exchange their preferences for a possible appointment. Because of the limited input capabilities of the small-sized devices information should be communicated as precisely as possible to overcome difficulties related to data input.

User with PDA and user at smart board. A user standing at a smart board has an opportunity to view large-scale alternatives of possible solutions. Nevertheless, after selection of an appropriate time and place, the appointments communicated to a PDA user have to be precise to reduce the complexity of the interaction with the small device.

Two users at one smart board. The interaction between two users sharing the same smart board is probably the most convenient form of interaction with respect to human to human communication. The huge display of a smart board can be divided into two separate views visualizing two different mental models.

Two users at two different smart boards. Unlike users at the same smart board, users at two different smart boards have the whole device for their own purpose. Alternative solutions can be easily visualized and communicated to the other communication partner in a larger scale than to a PDA.

After describing how and what kind of information mobile users exchange for the arrangement of appointments, the question arises how the positioning information (e.g. current user position or an appointment location) should be acquired and communicated. The proposed assistance system should provide location-based events, for instance availability of a smart board in the vicinity of our user. Therefore, localization information is needed.

Localization information. Continuous tracking of a user's position is not necessary, but rather her position has to be detected on demand in dedicated situations. Mobile users have to be able to send information about the place where they want to meet to their communication partners; e.g. they also may want to localize themselves when they got lost. The positioning information can be provided by wireless networks capturing the positions of mobile devices (cf. [23]). The assistance system provides an interactive map containing landmarks, e.g. booth numbers or names of snack bars, which can be chosen by clicking. Mobile users can identify their current position according to these landmarks themselves and send landmark positions to identify the place of initiated appointments.

This paper has outlined a number of ideas towards creating a mental model-based assistance tool for spatio-temporal planning in ubiquitous computing environments. However, many open issues remain:

- How can mental images be adequately modeled computationally when considering their quasi-pictorial nature?
- How can the representations of alternative models be adapted to a particular situation context?
- What are the advantages of using mental model-based approaches in this scenario compared to other approaches (such as statistical ones, or simple shortest-path algorithms)?
- Can alternatives for spatio-temporal problem solutions be generated individually according to the actual spatial knowledge of the user, e.g. for familiar / unfamiliar environments?

6 CONCLUSION

In the scope of the paper we have provided a concept of a mental model-based assistance system, which assists at solving dynamic spatio-temporal tasks. The proposed assistance system employs ubiquitous computing technologies in combination with mental model-based approaches to provide assistance for tasks that are beyond simple mental tractability. Mobile PDAs and stationary smart boards are employed as external media as they fit the requirements on user mobility and seamless interaction with mental images. From the described multi-user and multi-device scenarios it follows that device interaction capabilities are crucial for the amount of information to be exchanged. Finally, being aware of location-based events (e.g. vicinity and availability of stationary devices) contributes to the ubiquitous spatio-temporal assistance.

Eventually, the proof of the pudding is in the eating. It is through implementations of computational cognitive models for concrete assistance tasks, such as within the trade fair scenario sketched here, that they can prove that they have in fact the potential to improve human-computer communication, and to enable effective collaborative human-computer reasoning.

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