Temporal and Spatial Analysis to Personalise an Agent's Dynamic Belief, Desire, and Intention Profiles

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Abstract. The paper addresses the dynamic belief, desire and intention profiles that can be made of an agent following a particular route, for example through a city. It assumes that location of an agent has effects on his beliefs desires and intentions and that the history of agent’s mobility and observed states in different locations can be used to predict his future states if the location is being permanently observed. A formal spatial route language is introduced. Formal relationships between the intentional notions, and the spatial behaviour of an agent are defined. As an application an information agent architecture for reasoning about the intentions of the customers of a mobile location-based service is described.

1 Introduction

The simulation of social interactions in a complex natural environment by integrating intelligent agents and geographic information systems (GIS) have shown potential for improving resource management decision-making [1], [4], [6], [7], [8], [12], [13]. Spatial effect on a human or artificial agent’s behavior (beliefs, desires, intentions, etc.) is also known to be quite essential. Laboratory experiments [6] gathered survey data on the connection between goals, intentions, conflicts and actions and landscape content information provided by the GIS. The survey gathered over a thousand responses over a ten-month period to be used as a basis to develop beliefs, goals, intentions, and plans of actions for recreation groups using the area. Subsequent analysis is being undertaken to aggregate these responses into defined classes of agents characterised by goals, intentions, beliefs, perceived conflicts and then derive appropriate plans of action. Knowing what landscape features are preferred in terms of human recreation behaviour from the both lab experiments and on-site surveys, and knowing what these agents are viewing, where they are in the landscape, which settings are important to satisfying their recreational experience, and knowing cognitive goals, desires and intentions, behavioural rules can be derived and utilised for calibrating a set of artificial agents.

As agent behaviour often goes beyond purely reactive behaviour and nontrivial means are needed to describe and predict it. An attractive feature of intentional notions (cf. [5], [10], [11]) to describe agent behaviour is that these notions offer a high level of abstraction and have intuitive connotations.

It may be also very helpful to have capabilities to predict in which places of the environment certain inappropriate desires or intentions are likely to arise, either to avoid the arising of these intentions by preventing the occurrence of circumstances that are likely to lead to them, or, if these circumstances cannot be avoided, by anticipating consequences of the intentions.

An agent is assumed to decide to act and communicate based on its beliefs about its environment and its desires and intentions. These decisions, and the intentional notions by which they can be explained and predicted, generally depend on circumstances in the environment, and, in particular, on the information on where these circumstances just acquired by observations and communication, but also on information acquired in the other places. To be able to analyse the occurrence of intentional notions in the behaviour of an observed agent in a certain place of the environment, the observable behavioural patterns over different places in the environment, which the agent has already visited, form an empirical basis.

Received information (observed or communicated), and decisions to perform specific actions (or communications), constitute the input and output interface states of an agent to the environment in which the agent functions. Externally observed mobility of the agent are formalised as spatial sequences of the world states. A spatial route language is used to express properties on mobility behaviour.

In Section 2 the formal languages used in this paper are introduced. In Section 3, the assumptions made on the notions belief, desire and intention, and the way they interact with each other and with external notions are discussed and formalised: formal relationships between the intentional notions, and the external behaviour of an agent are defined. As an application, Section 4 describes an agent architecture for reasoning about the intentions of the customers of a mobile location-based service. Section 5 concludes.

2 Basic Concepts Used

In Sections 2 and 3 the temporal approach described in [9] is adopted as a starting point, and later on extended with elements referring to spatial aspects. A basic assumption on the ontologies, describing properties of world states, is that for each agent that is distinguished within the world, specific (sub)sets of ontologies of basic (atomic) world properties can be identified, according to properties that concern world state aspects *internal* to the agent, world state aspects *external* to the agent, or *interaction* aspects (input or output of the agent). On the basis of this assumption, ontologies for the agent's input, output and internal state are used, and for the state of the world external to the agent. It is assumed that state properties based on these ontologies describe the world state.

In the formalisation, for simplicity, we use predicate logic to specify both ontologies and properties. Ontology is specified as a finite set of sorts, constants (names) within these sorts, and relations and functions over these sorts (sometimes also called a signature). The union of two ontologies is also ontology. For a given state ontology, state properties are the (ground) propositions that can be expressed using the concepts of ontology. A state property is called atomic if no propositional connectives (i.e., *and*, *or*, *implies*, *not*) are used to express it.

The text below can be read without involving the formal details. To this end the formal details have been put aside in boxes, to be read only by readers interested in all technical details. For more conceptually interested readers, the text without the boxes should be readable as an independent conceptual text.

2.1 State Language

First, a language is used to represent facts concerning the actual state of the external world: ontology EWOnt. Some of the other (agent) ontologies will make use of EWOnt. Next, a language is used to represent facts concerning the state of the agent. The *agent input ontology* InOnt contains concepts for observation results and communication received. The following *input properties* are used for a given agent:

- a property expressing the observation result that some world statement holds; e.g., it rains	denoted by observation_result(p) where p denotes a state property of the external environment based on the ontology EWOnt
- a property expressing that agent C has communicated some world statement; e.g., agent C says to me that it rains	denoted by communicated_by(p, C) where p denotes a state property of the external environment based on the ontology EWOnt

Similarly, the *agent output ontology* OutOnt contains concepts to represent decisions to do actions within the external world, as well as concepts for outgoing communication and observations that the agent needs to obtain. The following *output properties* are used:

- a property expressing that the agent decides to perform action A; e.g., take an umbrella,	denoted by to_be_performed(A)
- a property expressing that the agent commu-nicates information to an agent C; e.g., I say to agent C that it rains	denoted by to_be_communicated_to(p, C) where p denotes a state property of the external environment based on the ontology EWOnt
- a property expressing that the agent decides to perform an observation to investigate the truth of a world state property; e.g., check whether it rains	denoted by by to_be_observed(p) where p denotes a state property of the external environment based on the ontology EWOnt

State properties, which model the interaction of the agent with its environment, are meta-properties: some of their arguments refer to state properties in an object-level language based on the ontology EWOnt. The *internal agent ontology* IntOnt is used for the internal (e.g., BDI) notions. The *agent interface ontology* is defined by InterfaceOnt = InOnt ∪ OutOnt; the *agent ontology* by AgOnt = InOnt ∪ IntOnt ∪ OutOnt, and the overall ontology by OvOnt = AgOnt ∪ EWOnt. The properties based on the overall state ontology are called *state properties*. All state properties based on a certain ontology Ont constitute the set SPROP(Ont).

2.2 Temporal and Spatial Language

Behaviour is described by changing states depending on time and on an agent's location. It is assumed that a state is characterised by the properties that hold in the state and those that do not hold.

Therefore, a *state* for ontology Ont is defined as an assignment of truth values to the set of atomic properties for Ont. The set of all possible states for ontology Ont is denoted by IS(Ont). We assume the time frame is the set of natural numbers or a finite initial segment of the natural numbers. An *overall trace* M over a time frame T is a sequence of states over the overall ontology OvOnt over time frame T. A *temporal domain description* W is a set of overall traces.

An *overall trace* M over a time frame **T** is a sequence of states $(M^t)_{t \in \mathbf{T}}$ in IS(OvOnt). Given an overall trace M, the state of the input interface of agent A at time point t is denoted by state(M , t, input(A)). Analogously, state(M , t, output(A)) denotes the state of the output interface of the agent at time point t, and state(M , t, internal(A)) the internal state. We can also refer to the overall state of a system (agents and environment) at a certain moment; this is denoted by state(M , t).

States can be related to state properties via the satisfaction relation that expresses which properties hold in which state (comparable to the holds-relation in situation calculus); e.g., "at South of Amsterdam at 11 o'clock it rained". The *spatial state language* SSL is built on location state information such as "at South of Amsterdam it rains", using the usual logical connectives and quantification (for example, over locations and state properties). Quantification over these entities makes the language quite expressive.

state(M, t, input(A)) |= φ denotes that $\varphi \in$ SPROP(InOnt) is true in this state at time t, based on the strong Kleene semantics (e.g., [2]). The set S(Ont) is the set of all state statements that only make use of ontology Ont. We allow additional language elements as abbreviations of statements of the spatial language. Especially important are additional language elements, defining SSL, to express location information:

location_has_property(x, y, p)

denotes that location (x, y) has property p. A special case is the state property p given by present(A), expressing that agent A is present.

location_has_property(x, y, present(A))

expresses that agent A is present at location (x, y). Using this, for example,

state(M, t, input(A)) |=
observation_result(location_has_property(x, y, p))

denotes that at time t the agent A's input has the information that it observed that location (x, y) has property p.

A *past statement* for trace variable M and time variable t is a temporal statement ψ(M , t) such that each time variable different from t is restricted to

For past statements, for every time quantifier for a variable t' a restriction of the form $t' \leq t$, or $t' < t$ is required within the statement. Note that for any past statement

the time interval before t. The set of past statements over ontology Ont w.r.t. M and t is PS(Ont, M , t).	$\psi(M, t)$ it holds: $\forall M \in W \;\forall t\; \psi(M_{[0,t]}, t) \;\Leftrightarrow\; \psi(M, t).$
To express that some state property has just become true, we use the qualifier *just*, denoted by ⊕. This is definable in other temporal terms: a state property has *just* become true at time t1 if and only if it is true at t1 and for some interval before t1 it was not true. Similarly it can be expressed that a state property just stopped to be true.	$\oplus\text{state}(M, t1, \textit{interface}) \models \varphi \;\equiv$ $\text{state}(M, t1, \textit{interface}) \models \varphi \;\wedge$ $\exists t2<t1 \;\forall t\, [\, t2 \leq t < t1 \Rightarrow$ $\text{state}(M, t, \textit{interface}) \not\models \varphi]$ $\oplus\text{state}(M, t1, \textit{interface}) \not\models \varphi \;\equiv$ $\text{state}(M, t1, \textit{interface}) \not\models \varphi \;\wedge$ $\exists t2<t1 \;\forall t\, [\, t2 \leq t < t1 \Rightarrow$ $\text{state}(M, t, \textit{interface}) \models \varphi$
A *route* R is defined as a mapping from distances d (on the route) to locations (x, y), e.g., after 300 m on this route you are at location (E, 5) on the map. Note that a route is defined in a time-independent manner.	A route R is specified by the predicate at_ distance_at_location (R, d, x, y) expressing that at route R after distance d you are at location (x, y).
A trace M of an agent walking in a city specifies an associated route R(M) in the following manner: at route after distance d you are at location (x, y) if and only if a time point t exists such that at t agent A has walked d from the start and is present at location (x, y). This abstracts from the specific trace the time information, keeping the spatial information.	Formally, at_ distance_at_location (R(M), d, x, y) ⇔ ∃ t state(M, t, EW) $\models$ distance_from_start(d) ∧ location_has_property(x, y, present(A))
Conversely, for a given route R the set of traces M (R) can be defined as those traces that follow route R.	Formally, $M(R) = \{\, M \mid R(M) = R \,\}$

3 External Representations of Beliefs, Desires and Intentions

In this section, the assumed notions of belief, desire, and intention, and their interdependencies are discussed and formalised. Agents are considered to which external representations of intentional notions can be attributed. The interdepenedencies depicted in Fig. 2 will be interpreted as spatial interdependencies. Statements expressed in the spatial language defined above will be analysed on whether or not they are adequate candidates to express these interdependencies of intentional notions. In particular, conditions are given that formalise when a spatial statement represents a belief, desire or intention.

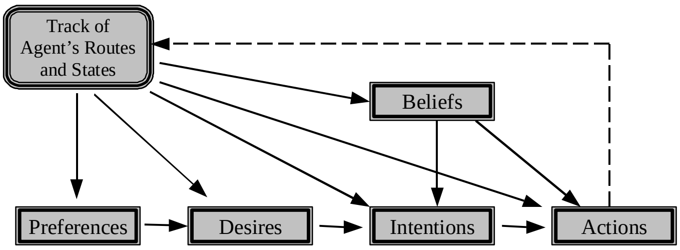

Fig. 1 Relationships between the BDI notions

A basic assumption made is that an agent's states functionally depend on the previous states and route(s) of the agent; i.e., two copies of the same agent build up exactly the same (internal) states if they have exactly the same inputs in the same time points and places. For a software agent, running on a deterministic machine, this Determinism Assumption can be considered a reasonable assumption. Differences between the behaviours of two copies of the same software agent will be created by their different histories, including having been at different locations. For most of the concepts defined below, this assumption is not strictly necessary, however, it is an assumption that strongly motivates the approach.

Comparing importance of temporal and spatial factors in determining behaviour we can say that depending on the context the importance can vary a lot. Consider example: there are two routes, one is related to temporal history of person A and the second one is related to the spatial history of the person B.

> *Person A (1981-1986 M.Sc. studies on Applied Mathematics; 1987-2000 – Ph.D. studies on Artificial Intelligence; 2001-2002 – Project Work on Ontology Engineering);*
>
> *Person B (M.Sc. studies on Applied Mathematics in University of Jyvaskyla; Ph.D. studies on Artificial Intelligence in Massachusetts Technological Institute; Project Work on Ontology Engineering in Vrije Universiteit Amsterdam).*

In this example the importance of spatial factor seem to be more powerful in the sense of providing more information about the person, which can be used for prediction of his future. Consider another example.

> *Person A (10:00 wants a cup of coffee; 15:00 wants to eat; 19:00 wants to watch TV News; 23:00 wants to sleep);*
>
> *Person B (wants a cup of coffee in train "Jyvaskyla-Helsinki" near Pasila station; wants to eat in Helsinki University Conference Room; wants to watch TV News in the Irish Pub in Downtown Helsinki; wants to sleep in "Scandic" Hotel).*

In this example we can see that temporal route is more predictive for the future behaviours because the person's desires in this case are more time - than spatially - related. In general, an integration of temporal (e.g., [9]) and spatial history routes would be the best background data for prediction of agent behaviour.

3.1 Beliefs

The first intentional notion to consider is the notion of belief, which usually is considered as an informational attitude, in contrast to motivational attitudes such as desires and intentions. Viewed from the spatial perspective an agent's beliefs originate from a location-based history of experiences; for example, observations and received communications in certain places. Beliefs affect future actions of the agent via their impact on other intentional notions (e.g., intentions or desires) that form the basis of actions. In our formalisation, beliefs are related to their route history.

In the simplest approach, beliefs (β) are based on information the agent has received by observation or communication in the past, and that has not been overridden by more recent information. This entails the first of our assumptions on beliefs: if the agent has received input in the past about a world fact, and no opposite input has been received since then, then the agent believes this world fact. The second assumption is the converse: for every belief on a world fact, there was a time at which the agent received input about this world fact (by sensing or communication), and no opposite input was received since then.

Before giving a temporal characterisation of the notion of belief an auxiliary definition is presented. The agent Ag gets information about a state property as *input* at time t if and only if it just received it at time t as an observation result or as information communicated by another agent B. This means that the agent has just received input that the state property is true at time point t.

Formally, let $p \in$ SPROP(Ont), then:

$\mathtt{Input}(p, t, M, Ag) \equiv$

$\oplus$state(M, t, input(Ag)) |=
observation_result(p)

$\vee\ \exists B \in$ AGENT $\oplus$state(M, t, input(Ag)) |=
communicated_by(p, B)

Here AGENT is a sort for the agent names. For simplicity of notation, often the fourth argument Ag will be left out: $\mathtt{Input}(p, t, M)$

Definition (Belief Statement)
The following characterisation of belief is based on the assumption that an agent believes a fact if and only if it received input about it in the past and the fact is not contradicted by later input of the opposite. Let $\alpha \in$ SPROP(Ont) be a state property over Ont. The temporal statement $\beta(M, t) \in TS$ is a *temporal belief statement* for state property α if and only if:

at each time point t and each trace M the statement $\beta(M, t)$ is true if and only if at an earlier time point t1 the agent received input that α is true and after this time point did not receive input that α is false. Sometimes this belief statement is denoted by $\beta_\alpha(M, t)$, to indicate it is a belief statement for α. In the specific case that $\beta(M, t)$ is a temporal belief statement, and, in addition, $\beta(M, t)$ is a temporal past statement (i.e., $\beta(M, t) \in PS(InOnt, M, t)$), over ontology InOnt, then it is also called a *historical belief statement* for α.

Formally, the temporal statement $\beta(M, t1) \in TS$ is a *temporal belief statement* for α if and only if

$\forall M \in W\ \ \forall t1\ [\beta(M, t1) \Leftrightarrow$

$\quad \exists t0 \leq t1\ [\ \mathtt{Input}(\alpha, t0, M) \wedge$

$\quad \forall t \in [t0, t1]\ \neg\ \mathtt{Input}(\sim\alpha, t, M)\ ]\ ]$

Here for state property α, the *complementary property* $\sim\alpha$ is defined as

$\sim\alpha = \alpha'$ if $\alpha = \neg\,\alpha'$
$\sim\alpha = \neg\,\alpha$ otherwise

Note that one particular historical belief statement for α is the temporal past statement $\mathtt{Belief}(\alpha, t, M) \in PS(InOnt, M,$

The temporal past statement
$\mathtt{Belief}(\alpha, t, M) \in PS(InOnt, M, t)$
is formally defined by

t) stating that 'at an earlier time point the agent received input that α is true and after this time point did not receive input that α is false'.

$$\exists t0 \leq t\ [\ \mathtt{Input}(\alpha, t0, M) \wedge \\ \forall t1 \in [t0, t]\ \neg\ \mathtt{Input}(\sim\alpha, t1, M)\ ]$$

If required, these assumptions can also be replaced by less simple ones, possibly in a domain-dependent manner; for example, taking into account reliability of sensory processes in observation or reliability of other agents in communication.

3.2 Desires and Intentions

Also motivational attitudes can be viewed from a spatial perspective. Our assumptions on intentions are as follows. In the first place, under appropriate circumstances an intention leads to an action: an agent who intends to perform an action will execute the action in the nearest known location where an opportunity (α) occurs. Moreover, the second assumption is that when an action or communication (A) is performed (θ), the agent is assumed to have intended (γ) to do that.

Definition (Intention Statement)

An *action atom* $\theta(M, t, Ag)$ is an atom stating that at time point t in trace M at the output of the agent Ag a specific generated action or communication can be found.

Let $\alpha \in$ SPROP(EWOnt) be an external state property and $\theta(M, t, Ag)$ an action atom. The temporal statement $\gamma(M, t) \in$ TS is called a *temporal intention statement* for action atom $\theta(M, t, Ag)$ and *opportunity* α if and only if the following conditions are fulfilled:

Formally, an *action atom* $\theta(M, t, Ag)$ is an atom of the form

state(M , t, output(Ag)) |= ψ

with ψ an output atom: an atom of the form to_be_performed(A),

to_be_communicated_to(p, B),

or to_be_observed(p).

Sufficiency condition for intention

If $\gamma(M, t)$ holds for a given trace M and time point t1, and at some earlier time point the agent received input that α holds and since then the agent did not receive input that α does not hold, then there is a time point t2 later than t1 at which the action $\theta(M, t2, Ag)$ occurs.

Formally, the *sufficiency condition for intention* is defined by:

$$\forall M \in W\ \forall t1\ [\ \gamma(M, t1) \wedge \\ \exists t0 \leq t1\ [\ \mathtt{Input}(\alpha, t0, M) \wedge \\ \forall t \in [t0, t1]\ \neg\ \mathtt{Input}(\sim\alpha, t, M)\ ] \\ \Rightarrow\ \exists t2 \geq t1\ \theta(M, t2, Ag)\ ]$$

Necessity condition for intention

If for a given trace M and time point t2 the action $\theta(M, t, Ag)$ occurs, then $\gamma(M, t1)$ holds at some earlier time point t1 and at a time point earlier than t1 the agent received input that α holds and since then until t1 the agent did not receive input that α does not hold.

Formally, the *necessity condition for intention* is defined by:

$$\forall M \in W\ \forall t2\ [\ \theta(M, t2, Ag) \Rightarrow \\ \exists t1 \leq t2\ \gamma(M, t1) \wedge \\ \exists t0 \leq t1\ [\ \mathtt{Input}(\alpha, t0, M) \wedge \\ \forall t \in [t0, t1]\ \neg\ \mathtt{Input}(\sim\alpha, t, M)\ ]]$$

In the specific case that the past statement $\gamma_P(M, t) \in PS(InOnt, M, t)$ is a temporal intention statement for $\theta(M, t, Ag)$ and opportunity α, it is also called a *historical intention statement* for action atom $\theta(M, t, Ag)$ and opportunity α.

The above definition formalises the case that all actions are intended actions. However, it is not difficult to define weaker variants. For example, if also unintended actions are allowed, the second (necessity) condition can be left out. An agent can desire states of the world as well as actions to be performed. When the agent has a set of desires, it can choose to pursue some of them. A chosen desire for a state of the world can lead to an intention to do an action if, for example, expected effects of the action (partly) fulfil the desire. The first assumption on desires is that, given a desire (δ), for each relevant action there is an additional reason (ρ), so that if both the desire is present and the agent believes the additional reason, then the intention to perform the action will be generated. Having this additional reason prevents the agent from performing actions that do not make sense in the given situation; e.g., actions with contradicting effects. The second assumption formalised in the definition below is that every intention is based on a desire (δ), i.e., no intention occurs without desire. Based on these assumptions, desire statements are defined as follows:

Definition (Desire Statement)

Let an external state property $\rho \in SPROP(EWOnt)$ and an intention statement $\gamma(M, t)$ be given. The temporal statement $\delta(M, t) \in TS$ is called a *temporal desire statement* for intention $\gamma(M, t)$ and *additional reason* ρ if and only if the following conditions are fulfilled:

Sufficiency condition for desire

If $\delta(M, t1)$ holds for a given trace M and time point $t1$, and at some earlier time point the agent received input that ρ holds and since then the agent did not receive input that ρ does not hold, then there is a time point $t2$ later than $t1$ at which the intention $\gamma(M, t2)$ occurs.

Necessity condition for desire

If for a given trace M and time point $t2$ the intention $\gamma(M, t2)$ occurs, then the desire $\delta(M, t1)$ holds at some earlier time point $t1$ and at a time point earlier than $t1$ the agent received input that ρ holds and since then until $t1$ the agent did not receive input that ρ does not hold.

Formally, the *sufficiency condition for desire* is defined by:

$$\forall M \in W \ \forall t1 \ [\delta(M, t1) \wedge \exists t0 \leq t1 \ [\mathtt{Input}(\rho, t0, M) \wedge \forall t \in [t0, t1] \ \neg \ \mathtt{Input}(\sim\rho, t, M)] \Rightarrow \exists t2 \geq t1 \ \gamma(M, t2)]$$

Formally, the *necessity condition for desire* is defined by:

$$\forall M \in W \ \forall t2 \ [\gamma(M, t2) \Rightarrow \exists t1 \leq t2 \ \delta(M, t1) \wedge \exists t0 \leq t1 \ [\mathtt{Input}(\rho, t0, M) \wedge \forall t \in [t0, t1] \ \neg \ \mathtt{Input}(\sim\rho, t, M)]]$$

If the past statement $\delta_P(M, t) \in PS(InOnt, M, t)$ is a temporal desire statement for intention $\gamma(M, t)$ and additional reason ρ, it is called a *historical desire statement* for intention $\gamma(M, t)$ and (additional) *reason* ρ.

As for intentions, weaker notions can be defined as well.

4 Tracking Spatial BDI Attributes in a Location Based System

In very general terms, the problem of predicting agent's states based on its spatial history can be described as follows (see Fig. 2). Given - set of routes M for the agent with observed agent state in different location points of each route; task – online prediction of agents next locations, BDI attributes and states for a new route.

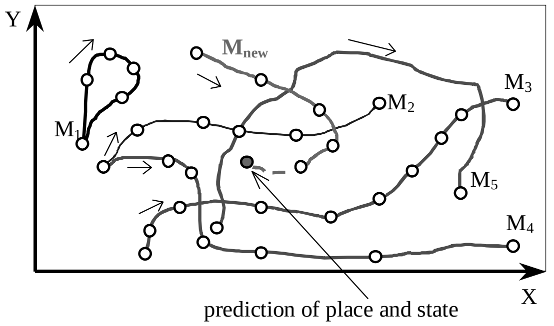

Fig. 2 Routes and states in agent's spatial history

In this chapter we are considering one case, where the necessary information about agent locations and states can be naturally tracked, observed or predicted. This case is a Mobile Location-Based Service (LBS), which is part of mobile commerce infrastructure.

In the general case, the location-based services can be defined as services utilizing the ability to dynamically determine and transmit the location of persons within a mobile network by the means of their terminals. From the mobile users' point of view, the LBSs are typically services accessed with or offered by her/his mobile terminal. Let us consider an example of LBSs: a visitor finding a suitable restaurant in a city being visited [14]. In this scenario you want to find a "near-by" restaurant where to eat. Using your mobile terminal you query for close moderately priced restaurants offering vegetable food. As a response, a map is presented on your terminal, displaying your current location and the locations of a few close restaurants offering vegetable food. By selecting a particular restaurant symbol on the map, you can get information about that restaurant, for example, the contact information and a lunch offer. After choosing one, you can ask for turn-by-turn navigation instructions to guide your way along the trip to the restaurant.

In mobile environment, a location service is one providing the location of the terminal for LBS. It computes the location estimate based on one or more positioning methods and delivers it to a service in a form of coordinates. Central component of the LBS itself is the content it provides, which can be divided into two categories: geographic data and location-based information [Virrantaus et al., 2001]. Geographic base data forms the data infrastructure of the services, consisting of the digital map data. Location based information is any value added information that can be joined to the base data, associated to a particular location. Geographic data is for example a street network and location-based information the information about restaurants.

4.1 Spatial BDI for Mobile Commerce Location-Based Application:

Here we are finding an analogy of the previous considerations of agent's spatial behaviour with the behaviour of a LBS customer.

Agent – mobile customer.

Agent's location – can be tracked by positioning infrastructure.

Observable agents actions – e.g. clickstream (points of interest) on a map delivered to the mobile terminal, calls and downloads of information about points of interest, appropriate orders, reservations, payments, etc. **-** can be tracked by LBS.

Spatial BDI Axiom: "If a customer has absolutely same *beliefs* about content and quality of two different services, and such content and quality fits his recent *desires*, then this customer *intents* to select nearest one to get service from it".

Agent's spatial beliefs

Spatial Belief Axiom – customer believes QoS(q), i.e., that in the same location he can get likely the same quality of service q as he used to get in this location before (observation and communication results); formally:

$$\begin{aligned}&\forall\, M \in W\ \ \forall t1\ [\beta_{\mathrm{location\_has\_property}(x,\,y,\ QoS(q))}(M\ ,\ t1) \Leftrightarrow\\&\quad \exists t0 \le t1\ \ [\ \mathtt{Input}(\mathrm{location\_has\_property}(x,\ y,\ QoS(q)),\ t0,\ M\ ) \wedge\\&\quad \forall t \in [t0,\ t1]\ \ \neg\ \mathtt{Input}(\sim\mathrm{location\_has\_property}(x,\ y,\ QoS(q)),\ t,\ M\ )\ ]\ ]\end{aligned}$$

Tracking spatial beliefs – based on the Spatial Belief Axiom, the customer's beliefs can be tracked based on his current location coordinates by analyzing the history of his observations and actions (e.g., orders) in this or neighbour locations (see Fig. 3).

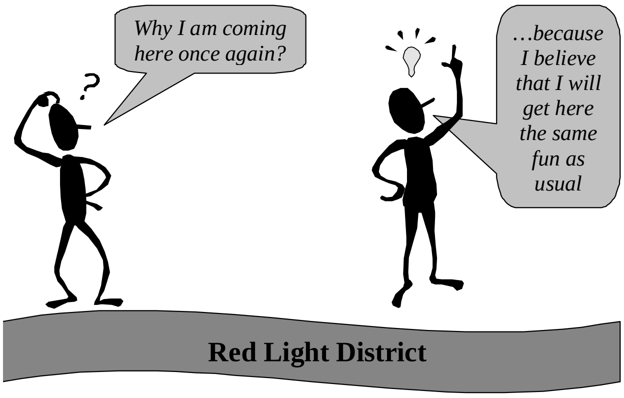

Fig. 3 Agent's spatial belief example

Agent's spatial desires

Spatial Desire Axiom – customer being in some location desires to get service q in some location x,y, i.e., he believes QoS(q), "turns his view" to location x,y and also believes that there is no such service $q1$ with better quality closer on his route to x,y; formally:

$$\forall M \in W\ \ \forall t, x, y, d, q\ \ \{\ at\_distance\_at\_location(R\ (M), d, x, y) \Rightarrow$$

$$[\ \delta_{get\_service(x,\ y,\ q)}(M\ , t)\ \Leftrightarrow$$

$$\exists t0 \leq t\ \ \forall\ t1 \in [t0, t]\ [\ (\ \beta_{location\_has\_property(x,\ y,\ QoS(q))}(M\ , t1)\ ) \wedge$$

$$\forall\ x1, y1, d1\ [\ (\ at\_distance\_at\_location(R\ (M), d1, x1, y1) \wedge (d > d1)\ ) \Rightarrow$$

$$\neg\ \exists q1\ (\ q1 < q \wedge\ \beta_{location\_has\_property(x1,\ y1,\ QoS(q1))}(M\ , t1)\ )\ ] \wedge$$

$$\exists t2 \in [t0, t]\ (\ \theta_{click\_location(x,\ y)}(M\ , t2)\ )\ ]\ \}$$

where $\theta_{click\_location(x,\ y)}(M\ , t2)$ denotes customers action «click to point x,y on his terminal screen», i.e. «turning view» to that point.

Tracking spatial desires – based on Spatial Desire Axiom, the customer's desires can be tracked based on types and coordinates of points of interest he clicks on the screen of mobile terminal (see Fig. 4).

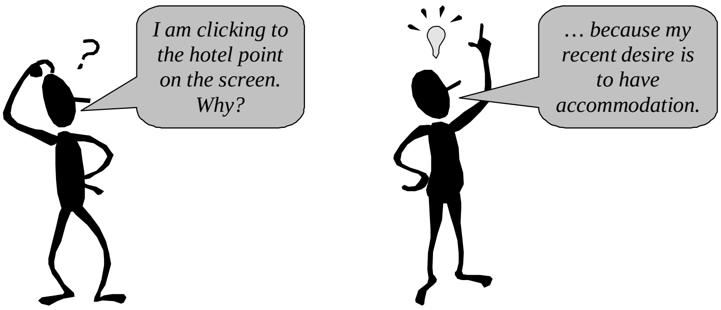

Fig. 4 Agent's spatial desire example

Agent's spatial intentions

Spatial Intentions Axiom – customer intends to get some service at a certain location, i.e. he desires to get this service, and he either order/reserve this service online or moves towards this service location point.

$$\forall M \in W\ \ \forall t, x, y, d, q\ \ \{\ at\_distance\_at\_location(R\ (M), d, x, y) \Rightarrow$$

$$[\ \gamma_{get\_service(x,\ y,\ q)}(M\ , t)\ ]\ \Leftrightarrow$$

$$\exists t0 \leq t\ \forall\ t1 \in [t0, t]\ [(\delta_{get\_service(x,\ y,\ q)}(M, t1)) \wedge \forall d1, d2\ \ at\_distance\_at\_location(R\ (M), d1, x, y)$$

$$\wedge$$

$$[\ \forall\ t2 \in\ [t1, t]\ [\ (\ at\_distance\_at\_location(R\ (M), d2, x, y) \wedge (d1 > d2 > d)\ )$$

$$\vee$$

$$\exists t3 \in [t1, t]\ (\ \theta_{order\_service\_online\ (q)}(\ M\ , t3)\ )\ ]\ ]\ ]\ ]\ \}$$

Tracking spatial intentions – based on Spatial Intentions Axiom, the customer's intentions can be tracked either based on the evidence of his ordering/reserving the desired service online or based on sequentially decreasing distance between customer location and desired service location (see Fig. 5).

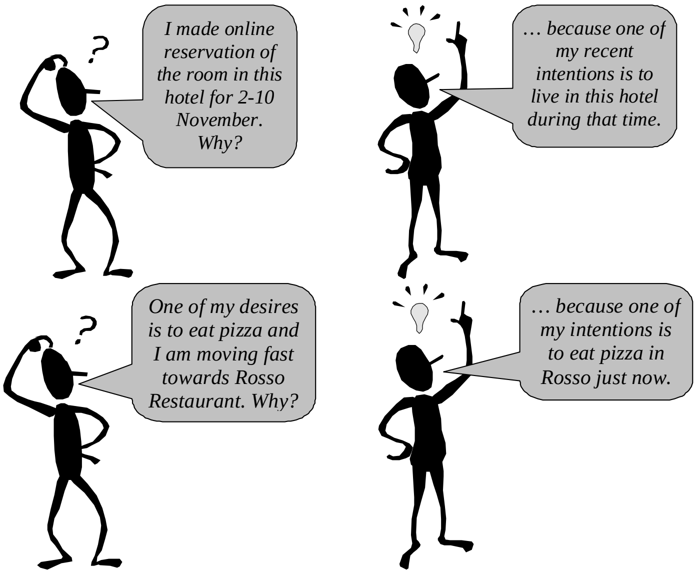

Fig. 5 Agent's spatial intentions examples

Agent's spatial actions:

Spatial Actions Axiom – a customer performs an action of getting some service, i.e. this service was intended, customer reaches the service location point and spends there at least minimal estimated time for this type of service or makes online electronic payment for this service.

$$\forall\ M \in W\ \ \forall t,x,y,d,q\ \{\ \text{at\_distance\_at\_location}(R\ (M),\ d,\ x,\ y) \Rightarrow$$

$$[\theta_{\text{get\_service}(x,\ y,\ q)}(M\ ,\ t)\ ] \Leftrightarrow$$

$$\exists t0 \leq t\ \forall\ t1 \in [t0,\ t]\ [(\gamma_{\text{get\_service}(x,\ y,\ q)}(M,\ t1)) \wedge \text{at\_distance\_at\_location}(R\ (M),\ d1,\ x,\ y) \wedge$$

$$[\ \forall ti \in\ [t2,\ t3] \subset [t1,\ t]\ [\ (\ \text{at\_distance\_at\_location}(R\ (M),\ 0,\ x,\ y) \wedge (\ t3 - t2 > \text{min\_time}(q))\ )$$

$$\vee$$

$$\exists t3 \in [t1,\ t]\ (\ \theta_{\text{pay\_for\_service\_online}\ (q)}(\ M\ \ ,\ t3)\ )\ ]\ ]\ ]\ \}$$

Tracking spatial actions – based on Spatial Actions Axiom, customer's actions can be tracked either based on the evidence of his electronic payment for the intended service online or based on a fact that customers coordinates are the same as intended service coordinates during minimal estimated time for this type of service (Fig. 6).

4.2 Mobile Commerce Location-Based Service Application

A Mobile Commerce (m-commerce) Location-Based Service Navigator (LBSN) helps its customers (mobile terminal users): (a) to navigate within unknown geographical locations, (b) to access information resources of real world services located in neighbourhood areas.

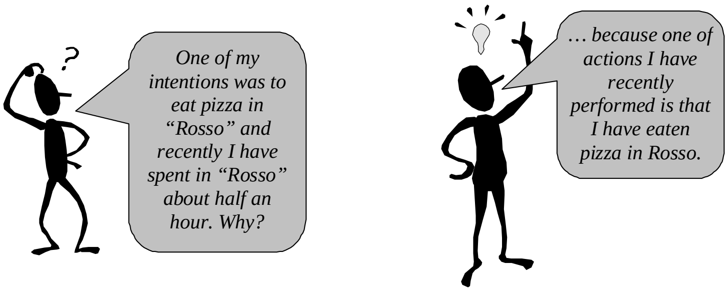

Fig. 6 Agent's spatial action example

The following transactions are typically expected from LBSN:

Changing Default Preferences (Input: built-in default preferences screen form, which consists of scale slices and types of services to be shown for each scale slice; Action: customer edits and saves form; Output: updated default customer preferences; Comment: for example at a Street Network scale slice customer wants to see museums, hotels and restaurants only, at a City Network scale slice he prefers to see only gasoline stations, at a Country Network scale he prefers to see only embassies).

Locating (Input: customer's request; Action: LBSN contacts positioning infrastructure, requests to locate customer, gets coordinates and delivers to customer; Output: customer's coordinates, four natural numbers (latitude, longitude, attitude, time point) according to agreed standard).

Showing Location (Input: customer's coordinates, scale of map visualizing; Action: LBSN selects appropriate geographical data, prepares it and delivers to customer's terminal; Output: screen with scaled map and pointed customer location on it; Comment: customer location supposes to be in the middle of screen, i.e. customer gets view of some scaled radius around his location).

Showing Services (Input: customer's coordinates, scale of map visualizing, preferences filter associated with scale; Action: LBSN selects appropriate geographical and service data, prepares it and delivers to customer's terminal; Output: screen with scaled map, pointed customer location on it and services, i.e. points of interest; Comment: all shown services are preliminary classified to types, displayed e.g. with different colours or different geometrical primitives for different type of service, and filtered against default user preferences).

Zooming (Input: screen with scaled map and pointed customer location on it, new scale of map visualizing; Output: screen with map updated according to a new scale and pointed customer location on it).

Intelligent Zooming (Input: screen with scaled map, pointed customer location and services on it, new scale of map visualizing, preferences filter associated with new scale; Output: screen with map and services updated according to a new scale and preference filter and pointed customer location on it; Comment: independently of selected scale LBSN is able to show in screen only limited number of points of interest, that is why the more big scale is used the more service points will be refused to be selected by preference filter).

Showing Point (Input: screen with scaled map, pointed customer location and services on it, customer's click to certain point of interest; Action: LBSN selects and downloads appropriate online data about requested service, prepares it and delivers to customer's terminal; Output: screen with online information about point of interest, e.g. recent offerings, prices, contact info, etc.).

Showing Route (Input: screen with scaled map, pointed customer location and services on it, customer's click to the point of interest on the map; Actions: LBSN discovers optimal routes from customer's location to selected point depending on map scale and available transport, prepares appropriate data and delivers it to customer's terminal; Output: screen with map with highlighted routes between the two points for all available transport facilities).

Call Point (Input: screen with online information about point of interest, customer's click to "call" button; Action: LBSN via mobile terminal dials telephone number of selected service; Output: Customer is connected to the point of interest.

Order Service (Input: screen with online information about point of interest, customer's click to "order" button; Action: LBSN via mobile terminal connects customer with appropriate service order web page of the selected service; Output: screen with online order form from the selected service web site).

4.3 Agent-Based Interpretation of the Location-Based Service Navigator

Location-Based Service Navigator (LBSN) for mobile customers is very similar to Autonomous Sensor Support for Agents (ASSA). Due to such autonomous sensor an agent is able to observe environment around his location, navigate within this environment, find, communicate with, get knowledge about, and services from other agents (services).

By keeping records of all transactions, ASSA is able to create really powerful collection of data about agents' behaviour. Appropriate data mining and knowledge discovery algorithms can be applied to discover useful patterns of each agent spatio-temporal behaviour and use these patterns for online prediction of agents' preferences, beliefs, desires, intentions and actions (see Fig. 2).

Now we can show what kind of information about agents ASSA can get from each transaction from the above-mentioned list of LBSN transactions:

1. *Changing Default Preferences* (ASSA gets explicitly agent's preferences, which can be treated as a set of possible agent's desires).
2. *Locating* (ASSA gets explicitly agent's location in different time points, i.e. can collect agent's routes within the environment and make grounded guesses based on this data about agent's spatial BDI).
3. *Showing Location* (ASSA gets explicitly the "picture of what the agent can see now", i.e. can discover some peace of the agent's knowledge).
4. *Showing Services* (ASSA gets explicitly data about "which services the agent can observe now", i.e. can discover some peace of the agent's knowledge).
5. *Zooming* (ASSA gets explicitly data about changing possible agents desires from one set of preferences to another one based on changes in scale. ASSA also gets new agent's view to the neighbouring environment).
6. *Intelligent Zooming* (ASSA gets explicitly data about changing possible agents desires from one set of preferences to another one based on changes in scale. ASSA also gets new agent's view to the services available in the neighbourhood).

7. *Showing Point* (ASSA gents explicitly focus of the agent's view, i.e. gets data about agent's desires, based on type of service the agent is observing now).
8. *Showing Route* (ASSA gets explicit information about agent's desire to move towards the selected point and to get appropriate service).
9. *Call Point* (ASSA gets explicit information about agent's intentions to get more information about appropriate service and agent's desire to get this service).
10. *Order Service* (ASSA gets explicit information about agent's intentions to get selected service).

5 Conclusions

The paper assumes that location of an agent effects on his beliefs desires and intentions and that the history of agent's mobility and observed states in different locations can be used to predict his future states if the location is being permanently observed. Formal spatial route language used in this paper is introduced. The assumptions made on the notions belief, desire and intention, and the way of their interactions are discussed and formalised: formal relationships between the intentional notions, and the spatial behaviour of an agent are defined. The case of using agent architecture for reasoning about the intentions of the customers of a mobile location-based service is also described.

The approach introduced here opens up a number of possibilities for further work. For example various electronic commerce applications are interested in personalizing their services to the customers by predicting and utilizing customer preferences. For location-aware applications the agent-based analogy of modelling customers' beliefs, desires and intention in tracked locations might be an important possibility. The model for beliefs, desires and intentions and their spatial dynamics can be made more complex if necessary. In particular, questions concerning revision and update of beliefs, desires and intentions can be addressed from the spatial perspective, for example in continuation of the exploratory investigations in modelling commitment strategies described in [3].

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