Qualitative Spatial Knowledge Acquisition Based on the Connection Relation

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***Abstract*—Research in cognitive psychology shows that the connection relation is the primitive spatial relation. This paper proposes a novel spatial knowledge representation of indoor environments based on the connection relation, and demonstrates how deictic orientation relations can be acquired from a map, which is constructed purely on connection relations between extended objects. Without loss of generality, we restrict indoor environments to be constructed by a set of rectangles, each representing either a room or a corridor. The term *fiat* cell is coined to represent a subjective partition along a corridor. Spatial knowledge includes rectangles, sides information of rectangles, connection relations among rectangles, and *fiat* cells of rectangles. Efficient algorithms are given for identifying one shortest path between two locations, transforming paths into *fiat* paths, and acquiring deictic orientations.**

***Keywords*-Deictic orientation; Connection relation; Indoor environments.**

I. Introduction

Human babies acquire connection relations before other spatial relations [8]; they first make a categorical distinction between contact and non-contact [1]. Qualitative distances between extended objects can be represented based on the connection relation [2]; the qualitative orientation relation can be understood through qualitative distance comparison [4]. Research in cognitive psychology shows that human babies acquire the spatial knowledge in a specific order: topological relations, orientation relations, and distance relations, [9]. The question raised in this paper can be stated as follows: given a spatial map which is purely based on the connection relation, can other spatial relations be acquired from this representation? We will construct a map for indoor environments only with the connect relation among rooms and corridors, and show how the deictic orientation instructions from one location to the other can be efficiently acquired. Without loss of generality we only consider rooms and corridors with four sides which can be approximated by rectangles. The method to acquire deictic orientation relations can be easily applied to spatial area with more than four sides, and curve-shaped corridors.

The following part is organized as follows: Section 2 briefly describes the knowledge acquisition problem of orientation instructions within indoor environments; Section 3 presents the spatial knowledge representation of indoor environments; Section 4 presents efficient algorithms which acquire orientation knowledge from connect-relation based spatial maps; Section 5 concludes the paper, and lists connections with other works.

II. Orientation within indoor environments

There are two different perspectives in describing orientations: the survey perspective and the route perspective [6]. In the survey perspective, orientation descriptions are constructed within the absolute orientation framework, e.g., *go south, at the next crossing, go west*; in the route perspective, orientation descriptions are constructed within the deictic orientation framework, e.g., *go ahead, at the next crossing turn left*. These descriptions are also called relative route descriptions. Acquiring orientation descriptions in the survey perspective requires information of absolute orientation. Such information is quite easy to obtain in outdoor environments where GPS is available. For in-indoor environments, it is reasonable to acquire relative orientation descriptions, not only due to the fact that GPS may not be available, but also due to the fact that many navigators do not know where the North is inside of indoor environments.

For classic mathematicians, orientation descriptions in natural languages are vague and imprecise. But not for cognitive psychologists: for them these descriptions serve as a window to explore mental spatial representations [12], which have systematical distortions from the external physical space [7]. Relative orientation knowledge is a useful route instruction which delineates a directed path in a distorted physical environment in mind. The basic components of relative route descriptions, addressed in this paper, are *go out of* <*somewhere*>, *go ahead till* <*somewhere*>, *turn left, turn right*. These components involve qualitative orientation instructions along with qualitative distance information.

In particular, people would like to hear pure qualitative spatial descriptions in indoor environments, as people are normally not so good at interpreting quantitative route descriptions, such as *go ahead for 15 meters, then turn clockwise 90 degrees* [5]. A preferred orientation description would be something like *go ahead and turn right at the end of the corridor* – even if the turning angle is less than 45 degrees, or the corridor has a strong curve. This

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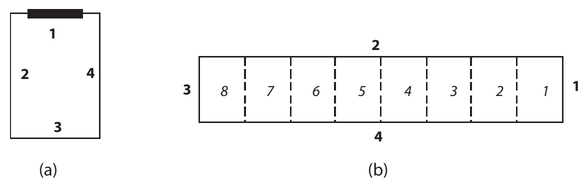

Figure 1. (a) A rectangle represents a room; (b) A rectangle represents a corridor, whose four sides are counterclockwise named from 1 to 4; *fiat* cells are named by the qualitative distance to the side with the name 1

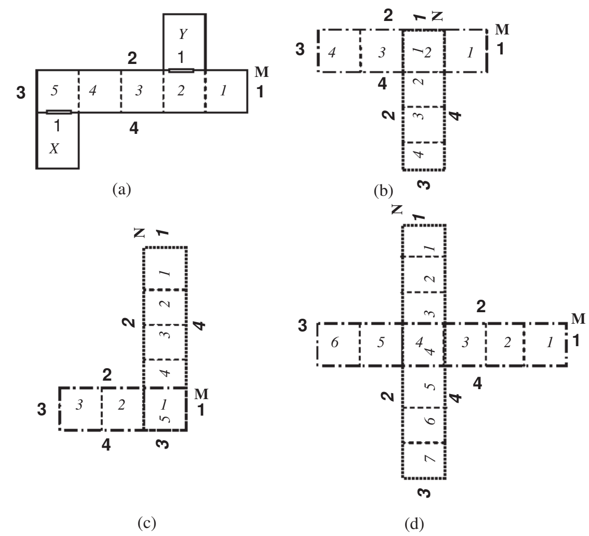

Figure 2. The connection relations between rooms and corridors

observation also explains why the fuzzy approach might fail in generating effective route descriptions in indoor environments. The problem addressed in this paper can be stated precisely as follows: with what kind of knowledge representations for indoor environments can qualitative deictic orientation knowledge be acquired, if the connection relation is primitive?

III. Spatial Representation of Indoor Environments

A. Rooms

The simplest component of an indoor environment is *room*. We assume that rooms have at least one door, and that rooms have four sides and are of rectangular shape. We name the four sides as 1, 2, 3, 4, and there must be a door in side 1, as illustrated in Figure 1(a). A room has a unique identification number, and a name for linguistic description, e.g., Prof. Helbig's office. Formally, we introduce the following definition.

Definition 1: $\mathcal{R}$ is the type of rooms. Let r be a room, ($r \in \mathcal{R}$), $r.\texttt{side\_1}$, $r.\texttt{side\_2}$, $r.\texttt{side\_3}$, $r.\texttt{side\_4}$ represent its four sides; $r.\texttt{side}$ represents one of its four sides; $r.\texttt{id}$ represents its identification number; $r.\texttt{name}$ represents its name.

B. Corridors

Rooms may be connected with each other by *corridors*. We also assume that corridors have rectangular shape, and their four sides are named counterclockwise from 1 to 4. Two end-sides of the corridor are named as 1 and 3, respectively; two long-sides of the corridor are named as 2 and 4, respectively. A corridor has a unique identification number, and may have a name for linguistic description. A corridor can be partitioned into a list of small rectangles, each has exactly two sides that coincide with side 2 and 4 of the corridor. These small rectangles are named as *fiat* cellsSides of *fiat* cells are named counterclockwise from 1 to 4, such that the sides coincided with its corridor have the same name (2 or 4). *Fiat* cells refer to different locations along a corridor, e.g., *end of the corridor, in front of the lift*, etc. Each *fiat* cell is assigned a natural number representing its qualitative distance to side 1 of the corridor; this number uniquely identifies a *fiat* cell, as illustrated in Figure 1(b). Formally, we introduce definitions as follows.

Definition 2: $\mathcal{C}$ is the type for corridors. Let c be a corridor ($c \in \mathcal{C}$), $c.\texttt{side\_1}$, $c.\texttt{side\_2}$, $c.\texttt{side\_3}$, $c.\texttt{side\_4}$ represent its four sides; $c.\texttt{side}$ represents one of its four sides; $c.\texttt{id}$ represents its identification number; $c.\texttt{name}$ represents its name.

Definition 3: $\mathcal{F}$ is the type for fiat cells. Let f be a fiat cell ($f \in \mathcal{F}$), $f.\texttt{side\_1}$, $f.\texttt{side\_2}$, $f.\texttt{side\_3}$, $f.\texttt{side\_4}$ represent its four sides; $f.\texttt{side}$ represents one of its four sides; $f.\texttt{cor}$ represents the corridor where it is located; $f.\texttt{dis}$ represents its qualitative distance to side 1 of $f.\texttt{cor}$.

C. Connections among rooms and corridors

By a room connecting with another room or a corridor, we assume that they share a common wall and that there is at least a door on the common wall, through which people can go. Otherwise, they might not know that they are connected. This can be easily represented by the shared side of two rectangles. For example, in Figure 2(a) Room X connects with Corridor M. The side 1 of Room X coincides with the side 4 of Corridor M. Formally, we define as follows.

Definition 4: Let $r, r_1, r_2 \in \mathcal{R}$, $c \in \mathcal{C}$. $r.\texttt{side\_}i$ connecting with $c.\texttt{side\_}j$ is written as $\mathsf{Con}(r, c) = (i, j)$; $c.\texttt{side\_}j$ connecting with $r.\texttt{side\_}i$ is written as $\mathsf{Con}(c, r) = (j, i)$; $r_1.\texttt{side\_}i$ connecting with $r_2.\texttt{side\_}j$ is written as $\mathsf{Con}(r_1, r_2) = (i, j)$, where $1 \leq i, j \leq 4$.

The location of a room in a corridor can be represented by the *fiat* cell in the corridor with which the room connects. We define the Loc function as follows.

Definition 5: Let $r \in \mathcal{R}$, $c \in \mathcal{C}$, r connects with the fiat cell in c whose qualitative distance is i, written as $\mathsf{Loc}(r, c) = i$.

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In Figure 2(a), Room X connects with the *fiat* cell of Corridor M whose qualitative distance is 5. We represent this as $\mathsf{Loc}(X, M) = 5$.

D. Connections between corridors

Connection relations between two corridors can be one of three types: 'T' type, 'L' type, and '+' type, as illustrated in Figure 2 (b), (c), (d), respectively. For all types we assume there are two intersected corridors. That is, there is an overlapped *fiat* cell. For example, in Figure 2(b) the *fiat* cell 1 in corridor N is overlapped with the *fiat* cell 2 in corridor M. The spatial structure between two intersected corridors can be delineated by their coincided sides and qualitative distances. For example, in Figure 2(b) Corridor M intersects with the *fiat* cell 1 of Corridor N; if a navigator is located in the intersection of Corridor N and Corridor M, and faces to side 1 of Corridor N, then she/he also faces to side 2 of Corridor M; in Figure 2(c) Corridor M intersects with the *fiat* cell 5 of Corridor N; if a navigator is located in the intersection and faces to side 3 of Corridor N, then she/he also faces to side 4 of Corridor M. Formally, we define as follows.

Definition 6: Let $c_1, c_2 \in \mathcal{C}$, c_1 intersects with the *fiat* cell in c_2 whose qualitative distance is i. The location of c_1 with regard to c_2 is defined as $\mathsf{Loc}(c_1, c_2) = i$.

Definition 7: Let $c_1, c_2 \in \mathcal{C}$, c_1 intersects with c_2, *fiat* cell f_1 in c_1 is overlapped with *fiat* cell f_2 of c_2 in such a way that $f_1.\texttt{side\_}i$ coincides with $f_2.\texttt{side\_}j$. Their side overlapping relation is defined as $\mathsf{Overlap}(c_1, c_2) \doteq (i, j)$.

Remark 1: Suppose the side 1 of *fiat* cell f_1 ($f_1.\texttt{side\_}1$) coincides with the side 4 of *fiat* cell f_2 ($f_2.\texttt{side\_}4$), then $f_1.\texttt{side\_}2$ coincide with $f_2.\texttt{side\_}1$, $f_1.\texttt{side\_}3$ must coincide with of $f_2.\texttt{side\_}2$, $f_1.\texttt{side\_}4$ must coincide with $f_2.\texttt{side\_}3$. Therefore, we use '$\doteq$' to roughly denote 'one of the (four) values is'. Generally, we have the following theorem.

Theorem 1: Let $c_1, c_2 \in \mathcal{C}$, $\mathsf{Overlap}(c_1, c_2) \doteq (i, j)$. For any natural number k, i.e., $k \in \mathbb{N}$, $\mathsf{Overlap}(c_1, c_2) \doteq ((i + k - 1)\ mod\ 4 + 1, (j + k - 1)\ mod\ 4 + 1)$.

E. Indoor Map based on the connection relation

An indoor map can be represented as the connection relations among rooms and corridors, in particular with the partial functions Con, Loc and Overlap whose signatures are listed as follows.

Signature 1: Let $\mathcal{S}$ be the set of 1, 2, 3, 4; $\mathbb{N}$ be the set of natural numbers.

$$\begin{aligned}
&\mathsf{Con} : \mathcal{R} \times \mathcal{C} \to \mathcal{S} \times \mathcal{S}\\
&\mathsf{Con} : \mathcal{R} \times \mathcal{R} \to \mathcal{S} \times \mathcal{S}\\
&\mathsf{Con} : \mathcal{C} \times \mathcal{R} \to \mathcal{S} \times \mathcal{S}\\
&\mathsf{Loc} : \mathcal{R} \times \mathcal{C} \to \mathbb{N}\\
&\mathsf{Loc} : \mathcal{C} \times \mathcal{C} \to \mathbb{N}\\
&\mathsf{Overlap} : \mathcal{C} \times \mathcal{C} \to \mathcal{S} \times \mathcal{S}
\end{aligned}$$

Example 1: In Figure 2(a), there are one Corridor M, two rooms X and Y. Room X connects with the *fiat* cell 5 of M, Y connects with the *fiat* cell 2 of M. side 1 of X connects with side 4 of M; side 1 of Y connects with side 2 of M. The map is therefore,

$$\begin{aligned}
&\mathsf{Con}(X, M) = (1, 5)\\
&\mathsf{Con}(Y, M) = (1, 2)\\
&\mathsf{Loc}(X, M) = 5\\
&\mathsf{Loc}(Y, M) = 2
\end{aligned}$$

Example 2: In Figure 2(b), there are two Corridors M and N, Corridor M intersects with the *fiat* cell 1 of N, $f_{N,1}$; N intersects with the *fiat* cell 2 of M, $f_{M,2}$. The side 1 of $f_{N,1}$ coincides with the side 2 of $f_{M,2}$. The map is therefore,

$$\begin{aligned}
&\mathsf{Loc}(M, N) = 1\\
&\mathsf{Loc}(N, M) = 2\\
&\mathsf{Overlap}(N, M) \doteq (1, 2)
\end{aligned}$$

IV. Acquiring Relative Orientation Knowledge Based on the Connection Relations

Acquisition of relative orientation knowledge in indoor environments can be separated into two steps: the first step is to find a path between the start location and the target location; the second step is to acquire relative orientations from the start location to the target along the path. This spatial knowledge acquisition process within indoor environments is normally not supported by GPS, therefore, the navigator needs to remember all the orientation knowledge at the beginning. This leads to some differences from orientation knowledge acquisition in outdoor environments. One important property which shall be emphasized in the indoor spatial knowledge acquisition is that the route instructions shall be short.

A. Find one of the shortest paths

In indoor environments, a path is a sequence of rooms and corridors. Let A_1 and A_n be the start location and the target location, respectively. A path between A_1 and A_n is a sequence $A_1, A_2, \ldots, A_{n-1}, A_n$ such that for any $i(\ 1 \le i \le n-1)$ navigators can move between A_i and A_{i+1}. Formally, we introduce Path function as follows.

Definition 8: Let A_1 and A_n be two locations. A path between A_1 and A_n is a sequence $A_1, A_2, \ldots, A_{n-1}, A_n$ such that for any i, $1 \le i \le n-1$, either (A_i, A_{i+1}) or (A_{i+1}, A_i) is in the domain of one of the partial functions Con, Loc and Overlap. $\mathsf{Path}(A_1, A_n)$ is the set of all paths between A_1 and A_n.

$$\begin{aligned}
\mathsf{Path}(A_1, A_n) \quad &\stackrel{def}{=} \{[A_1, A_2, \ldots, A_{n-1}, A_n] |\\
&\forall i : 1 \le i \le n-1, (A_i, A_{i+1}) \in \mathsf{DOM}\\
&\qquad\qquad \vee (A_{i+1}, A_i) \in \mathsf{DOM}\}
\end{aligned}$$

f.dom refers to the domain of function f.
DOM = Con.dom ∪ Loc.dom ∪ Overlap.dom

Theorem 2: $\mathsf{Path}(A_1, A_n) = \mathsf{Path}(A_n, A_1)$

Proof is trivial.

Remark 2: The path between two locations is understood as with no direction. To guarantee this property, we define the path as the set of all sequences (routes) from one location to the other.

Example 3: In Figure 2(a), [X,M,Y] is a path between Room X and Room Y, i.e., [X,M,Y]∈ Path(X,Y), because the following values are defined: Con(X, M) and Con(Y, M).

Given two locations inside of an indoor environment, one of the shortest paths between them can be identified by the breadth-first search algorithm as follows.

Algorithm 1: Search one of the shortest paths between two places, if exists

```
input : A map M, two different places A_1 and A_n
output: one of the shortest paths between A_1 and A_n,
        if there is a path between them; or NoPath if
        there is no path between them

All ←get all of the rooms and corridors from M;
Queue ← [A_1];
NotUsed ← All − {A_1};
i ← 0;
while i in the domain of Queue do
    if Queue(i) = A_n then
        Path ←get all the ancestors of A_n;
        return Reverse(Path)
    Temp ←get all of the the rooms and corridors
    connected with Queue(i);
    Temp ← Temp ∩ NotUsed;
    if Temp ≠ ∅ then
        set Queue(i) as the ancestor of each element
        in Temp ;
        append all elements in Temp  to Queue ;
        NotUsed ← NotUsed − Temp;
    i ← i + 1;
return NoPath
```

Let n be the total number of rooms and corridors, $\mathsf{ConnectWith}(X)$ be the number of rooms and corridors that X directly connects with, and K be the maximum number of any $\mathsf{ConnectWith}(X)$. In indoor environments we assume K is not related with n. That is, K is a constant. The computational complexities of space and time of this algorithm are $\mathcal{O}(Kn) = \mathcal{O}(n)$.

B. Fiat *path*

To ease the acquisition of a relative orientation knowledge along a path, we introduce the term of *fiat* path. Each path has a *fiat* path which is a sequence of rooms and *fiat* cells of corridors. If C is a corridor in the path, and a navigator enters C at its *fiat* cell i, and leaves C at its *fiat* cell j, C is replaced with $C.i, C.j$. Formally, we define as follows.

	$p=1$	$p=2$	$p=3$	$p=4$
$n=1$	-	*turn left*	*turn around*	*turn right*
$n=2$	*turn right*	-	*turn left*	*turn around*
$n=3$	*turn around*	*turn right*	-	*turn left*
$n=4$	*turn left*	*turn around*	*turn right*	-

Table I
TURNING INSTRUCTIONS INSIDE OF A ROOM OR A CORRIDOR; '-' MEANS THAT TURNING IS NOT REQUIRED

Definition 9: Let path $P = [A_1, A_2, \ldots, A_{n-1}, A_n]$, its *fiat* path, written as $f\mathsf{Path}(P)$, is defined as follows.

$$f\mathsf{Path}(P) \stackrel{def}{=} [f(A_1), f(A_2), \ldots, f(A_{n-1}), f(A_n)]$$
$$\begin{cases} f(A_i) = A_i & A_i \in \mathcal{R} \\ f(A_i) = A_i.s, A_i.e & Cond_2 \\ f(A_1) = A_1.s & Cond_3 \\ f(A_n) = A_n.e & Cond_4 \end{cases}$$

$Cond_2 : A_i \in \mathcal{C} \wedge \mathsf{Loc}(A_{i-1}, A_i) = A_i.s \wedge \mathsf{Loc}(A_{i+1}, A_i) = A_i.e, 2 \le i \le n-1$
$Cond_3 : A_1 \in \mathcal{C} \wedge \mathsf{Loc}(A_2, A_1) = A_1.s$
$Cond_4 : A_n \in \mathcal{C} \wedge \mathsf{Loc}(A_{n-1}, A_n) = A_i.e$

C. Spatial reasoning on acquiring relative orientation knowledge

Given a map and a *fiat* path, we can acquire relative orientation knowledge. The task can be described as follows: let $[A_i, A_{i+1}]$ be a path segment along a path and $[f(A_i), f(A_{i+1})]$ its corresponding *fiat* path segment, describe a relative route description from location A_i to A_{i+1}, $(1 \le i \le n-1)$.

1) Room A_i and Room A_{i+1}: Suppose now the navigator is in Room A_i and faces to side m of A_i, which connects with Room A_{i+1} such that $\mathsf{Con}(A_i, A_{i+1}) = (p, q)$, that is, side p of Room A_i connects with side q of Room A_{i+1}. Relative route instruction in this case has the form $<$*instruction for turning in* $A_i >$*, go out of the room*". At the end, the reasoning process shall acquire the knowledge of the navigator's facing direction in A_{i+1}, if A_{i+1} is not the target place.

In our proposed data model, sides of rooms and corridors are named counterclockwise with 1,2,3,4. So, given the starting facing side n and the target facing side p in the same location, we can acquire the instruction for turning with the matrix as shown in Table 1. If we calculate the value of $(n-p)\ mod\ 4$, we obtain a matrix as shown in Table 2.

The algorithm for generating turning instruction is quite simple, as illustrated in Algorithm 2.

When the navigator arrives in A_{i+1}, we need to know to which side she/he is now facing. As we have

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	$p=1$	$p=2$	$p=3$	$p=4$
$n=1$	0	3	2	1
$n=2$	1	0	3	2
$n=3$	2	1	0	3
$n=4$	3	2	1	0

Table II
TURNING INSTRUCTIONS CAN BE ENCODED WITH A CYCLIC GROUP, 0:-;1:*turn right*; 2: *turn around*; 3:*turn left*

Algorithm 2: Acquiring turning instructions inside of a room or corridor

input : facing side n, facing side p
output: turning instruction

$v \leftarrow (n-p)\ mod\ 4$;
switch *v* **do**
  case *0 return* "-";
  case *1 return "turn right"*;
  case *2 return "turn around"*;
  case *3 return "turn left"*;

$\mathsf{Con}(A_i, A_{i+1}) = (p, q)$, we know that after entering Room A_{i+1}, the navigator is back to side q of A_{i+1}. Therefore, she/he is facing to the opposite side of q, written as $\mathsf{Opp}(q)$, This can be easily computed by the formula as follows: $\mathsf{Opp}(q) = \begin{cases} q+2 & \text{if } q \leq 2 \\ q-2 & \text{if } q > 2 \end{cases}$.

The computational complexities for generating turning instruction, as well as updating facing direction, are $\mathcal{O}(1)$.

2) Room A_i and Corridor A_{i+1}: Suppose now the navigator is in Room A_i and faces to side m of A_i, who needs to enter Corridor A_{i+1}, and may go along the corridor to a certain location to enter A_{i+2}. We know $\mathsf{Con}(A_i, A_{i+1}) = (p, q)$ and $\mathsf{Loc}(A_i, A_{i+1}) = s$, and let the *fiat* path segment of $[A_i, A_{i+1}]$ be $[A_i, A_{i+1}.s, A_{i+1}.e]$.

The relative orientation knowledge in this case consists of two parts: the first part is on how to move from A_i to $A_{i+1}.s$; the second part is on how to move from $A_{i+1}.s$ to $A_{i+1}.e$. As the sides of *fiat* cells are named counterclockwise and such that two of them coincide with sides of corridors, the first part is the same as moving from room to room. Suppose the navigator is now in $A_{i+1}.s$ facing to side n, we need to give relative route instructions which help her/him to arrive at $A_{i+1}.e$. As *fiat* cells are named by numbers in such a way that the smaller the number is, the closer this cell is to the side 1 of the corridor, we can use this qualitative distance comparison method to figure out the turning instruction at $A_{i+1}.s$ as follows: if $s < e$, $A_{i+1}.s$ is nearer to side 1 of the corridor than $A_{i+1}.e$ is, so the navigator shall turn to side 3 of the corridor, which is defined as the same side of this *fiat* cell; if $s > e$, $A_{i+1}.e$ is nearer to side 1 of the corridor than $A_{i+1}.s$ is, so the navigator shall turn to side 1 of the corridor. So, we can use Algorithm 2 to generate turning instruction at $A_{i+1}.s$. Instruction for moving from $A_{i+1}.s$ to $A_{i+1}.e$ is quite simple, just *go ahead* plus some landmark information along this *fiat* path segment.

3) Corridor A_i and Room A_{i+1}: Suppose now the navigator is at *fiat* cell s of Corridor A_i and faces to side m of A_i ($A_i.\mathtt{side\_}m$), and needs to enter Room A_{i+1}. In this case she/he may go along the corridor first and then perform a turning to enter A_{i+1}. We know $\mathsf{Con}(A_i, A_{i+1}) = (p, q)$ and $\mathsf{Loc}(A_{i+1}, A_i) = e$, and let the *fiat* path segment of $[A_i, A_{i+1}]$ be $[A_i.s, A_i.e, A_{i+1}]$. No new algorithms are needed to acquire relative orientation knowledge from $A_i.s$ to $A_i.e$ and from $A_i.e$ to A_{i+1}.

4) Corridor A_i and Corridor A_{i+1}: Suppose now the navigator is at *fiat* cell s of Corridor A_i and faces to side m of A_i ($A_i.\mathtt{side\_}m$), and needs to enter Corridor A_{i+1}. We know that Corridor A_i and Corridor A_{i+1} overlaps in such a way that *fiat* cell u of A_i, $f_{i,u}$, connects with A_{i+1}, *fiat* cell w of A_{i+1}, $f_{i+1,w}$, connects with A_i, side p of $f_{i,u}$ coincide with side q of $f_{i+1,w}$. That is, $\mathsf{Loc}(A_{i+1}, A_i) = u$, $\mathsf{Loc}(A_i, A_{i+1}) = w$, $\mathsf{Overlap}(A_i, A_{i+1}) \doteq (p, q)$. In the most complicated case, the *fiat* path segment of $[A_i, A_{i+1}]$ is in the form of $A_i.s, A_i.u, A_{i+1}.w, A_{i+1}.e$, where the value e can be obtained from $[A_{i+1}, A_{i+2}]$, we can reuse above algorithms to acquire relative orientation knowledge between *fiat* cells within a corridor and between coincided *fiat* cells of different corridors.

The whole algorithm is illustrated in Algorithm 3, whose computational complexity is the same as that of algorithm 1: $\mathcal{O}(n)$.

V. CONCLUSIONS, DISCUSSIONS, AND OUTLOOKS

Spatial knowledge representation of orientation relations usually requires to represent a point-based orientation reference framework. A survey can be found in [11]. This paper presents a novel method showing that how deictic orientation relations between extended objects can be acquired without using orientation reference framework.

The advantages of this representation are as follow: this method is theoretically supported by results from cognitive psychology; practically this representation fills one gap between quantitative sensor representation, which are objective, and acquired by laser scanners, cameras, and spatial linguitistic descriptions, which are subjective, and delineate a *fiat* world [10]. By introducing granularities of *fiat* cells, cognitive agents will talk about a space as people do. Obtaining a map only based on the connection relation is an open question. However, cognitive psychology again provides useful guidelines: infants' developement of object concepts is closely related with their developement of spatial relations [8]. On the other hand, if a full environment map is available, the presented orientation acquisition method can be understood as a wayfinding method without GPS information, e.g., in the tunnel, under bad weather.

Algorithm 3: Acquiring relative orientation knowledge on a floor

```
input : starting room, starting facing, target room,
        three tables
output: relative route instruction
Path ← apply Algorithm 1 to get one shortest paths;
fiatPath ← turn Path into fiat path;
Facing ←starting facing;
Route ←“”;
repeat
    Loc1 ← first(fiatPath );
    Loc2 ← second(fiatPath );
    if (type(Loc1)≠type(Loc2)
    ∨type(Loc1)=type(Loc2)=R) then apply
    Algorithm 2 in Loc1, append result to Route;
    append go ahead to Route;
    else
        if Loc1 and Loc2 in the same corridor then
            determine targeting facing by distance
            comparison;
            apply Algorithm 2 in Loc1, append result
            to Route;
            append go ahead and landmark information
            to Route;
    updating Facing in Loc2;
    pop(fiatPath);
until length(fiatPath)≤ 1;
EndFacing ← get the side of current location
connecting with target room;
v ← (Facing − EndFacing) mod 4;
switch v do
    case 0 append the target room is in front of you to
    Route;
    case 1 append the target room is at the right side
    of you to Route;
    case 2 append the target room is back to you to
    Route;
    case 3 append the target room is at the left side of
    you to Route;
return Route;
```

Indoor spatial environments may be complex, some have layer-structures on a floor, some have concave shaped rooms. The method presented in this paper can be extended by considering granularities and more sides of spatial objects. For example, Yuan and Schneider [13] proposed a 3D method, LEGO representation, to construct maps of indoor environments. By extending rectangles into hexahedrals, we can develop similar method for 3D indoor environments. The path-finding algorithm for higher dimensional environment shall be more complex.

We can use the connection relation as primitive to recognize changed environment, [3]. However, it is still an open issue to explore unknown environments with this primitive relation. It is a piece of interesting future work for us to extend current work into robotics: How can a robot explore unknown environments based on the connection relation and some primitive perceptions and actions? There is already some similar work in the literature, e.g., spatial models developed at http://jrobot.gforge.inria.fr are based on primitive actions.

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