**Preprints of the 21st IFAC World Congress (Virtual)**
**Berlin, Germany, July 12-17, 2020**

# Mobile Robot Navigation Based on Regionalized Spatial Knowledge Representation and Reasoning ⋆

**Chaoliang Zhong ∗ Shirong Liu ∗ Qiang Lu ∗ Botao Zhang ∗ Jian Wang ∗ Qiuxuan Wu ∗ Farong Gao ∗**

∗ *School of Automation, Hangzhou Dianzi University, Zhejiang, 310018, China (e-mail: (zhongchaoliang,liushirong,lvqiang,billow,wangjian,wuqx,frgao)@hdu.edu.cn).*

**Abstract:** A regionalized environmental knowledge model (REKModel) is presented to describe the environment in the paper. The REKModel is a hierarchical structure in which small regions are grouped together to form superordinate regions. The REKModel is intrinsically hierarchical iterative and nested. Thus an extended nested-graph(ENG) is proposed to construct REKModel. An biomimetic navigation system for mobile robots is presented that is inspired by the fine-to-coarse planning heuristic, a human wayfinding strategy. A online fine-to-coarse pathfinding algorithm designed here allows robots to derives the route with decreasing the level of detail along the route. By using spatial information at different levels of detail for close and coarseness for distance, the memory load and plan complexity are all reduced. The simulation on MobileSim platform verifies the effectiveness and feasibility of the navigation system.

*Keywords:* Robot Navigation, Path Planning, Regionalized Spatial Knowledge Representation and Reasoning

## 1. INTRODUCTION

Navigation is an essential issue for mobile robots. Mobile robot is required to determine its own location and plan a path towards some destinations by using internal spatial representation of environment, and moves to a particular location guided by a navigation mechanism. The research on human navigation ability mainly focuses on two aspects: the internal representation of environment in the memory system and the navigation mechanism in the process of human activities. In the field of robot research, metric map(Kuric et al. (2017)) and topological map(Kostavelis and Gasteratos (2015)) are often used to model the environment. However, the experimental results of environment sketch(Gopal et al. (1989)), environment recall(Voicu (2003)), navigation experiments in virtual environments(Wiener et al. (2004)), linguistic interact experiments(Spiers and Maguire (2008)), as well as brain FMRI(Boccia et al. (2014)) show that environment in memory system is not expressed as a whole, but organized into a hierarchical structure with spatial objects such as regions, landmarks and positions as unit nodes. Neither metric map nor topology map can describe such structure.

It is found that three heuristic strategies play an important role in human navigation process, including fine-to-coarse (FTC) pathfinding strategy(Wiener et al. (2004),Wiener and Mallot (2003)), clustering strategy(Gallistel and Cramer (1996)) and minimum decision load strategy(O'Neill (1992)). The strategy of finding path from fine to coarse makes the mobile adopt different planning strategies for the distance of environmental information when planning path. For the near, the mobile obtains detailed environmental information for fine path planning, while for the far, the mobile makes rough path planning according to the coarse-grained environmental information. This routing strategy reduces the computational memory load and computational complexity. When there are multiple targets, the clustering strategy makes the mobile arrive at the most abundant target first. The minimum decision load strategy makes the mobile planning always tend to minimize the complexity of the planning.

Inspired by the ability of human navigation, this paper attempts to integrate environment representation and navigation mechanism to construct a robot navigation system. In this paper, a regionalized environmental knowledge model (REKModel) is proposed to describe the multi-layer nested environmental knowledge. Extended Nested-Graph(ENG) are proposed to describe the REKModel. Each node in the model represents an environmental object, such as a landmark, a region, a place, and so on. The edges between nodes represent the relationships between nodes. The Meretopological Theroy and the Minimizing Bounding Rectangle (MBR) model are introduced to describe the topological and directional relations between nodes. It makes the environmental information from the description level of data to the semantic knowledge level, and is easy for the spatial reasoning and understanding of robots. Then a bionic navigation system based on fine-to-coarse (FTC) pathfinding strategy is designed and implemented, and a fine-to-coarse pathfinding algorithm is

⋆ This work was supported in part by the Natural Science Foundation of Zhejiang Province under Grant LY18F030008 and 2017C31004, and in part by the Key research and development program of Zhejiang province China under Grant 2019C04018.

proposed to dynamically plan the path from the current position of the robot to the target. Based on REKModel, the algorithm can plan the environment around the robot precisely and plan the environment far away coarsely. With the movement of the robot, the dynamic online path planning makes the robot always have a fine path planning when moving to the target along the path, until reaching the target.

## 2. REGIONALIZED REPRESENTATION OF ENVIRONMENTAL KNOWLEDGE

### *2.1 Representing REKModel with Extended Nested-graph*

Abundant research results(Wiener et al. (2004),Wiener and Mallot (2003)) have led to the hierarchical theories of region-based spatial representations in memory. Hierarchical theories demonstrated that spatial representations are regionalized and nested with multi-levels. Such spatial representations are organized in a graph-like structure where regions are grouped together to form upper level regions. Fig.1 shows an example of the REKModel with a small spatial environment. The model involves two primary types of components: the nodes and the links between nodes. Region nodes are formed by means of the lower level nodes. Common phenomenological concepts, such as “bed”,“room”,“house”,“town”,“region”,“place”, are recognized and described in terms of “spatial objects” or “spatial entities”. Based on nested graph, this paper proposes extended nested graph to describe the REKModel.

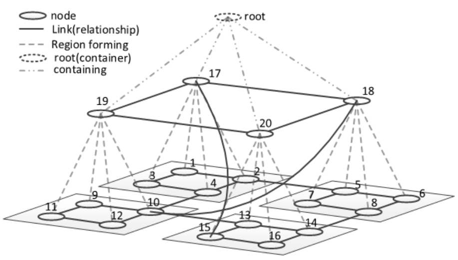


Fig. 1. An example of a regionalized presentation environment.

Nested graph is a graph that contains nodes that are graphs, i.e. a nested sub-graph can be included in another graph, and thus nested graph is a recursive and hierarchical model.

**Definition1. (Nested Graph)** Assume that $C$ is a class set of graphs. A nested graph is defined as a couple $G = (N, E)$, where:

(1) $N = \{G_1, G_2, \cdots, G_k\}$ is a finite set of Nodes of $C$ such that $\forall i(G_i \in C)$ and $N \subset C$ .

(2) $E$ is a set of edges of $G$, where $E \subseteq N \times N$.

Nested graphs are not sufficient to describe the link information between different layers of nodes. So we define a extended nested-graph(ENG) model.

**Definition2. (Extended Nested-Graph)** Let $C$ is a class set of graphs. A extended nested graph is defined as a couple $G = (N, R)$, where:

(1) $N = \{G_1, G_2, \cdots, G_k\}$ is a finite set of Nodes of $C$ such that $\forall i(G_i \in C)$ and $N \subset C$ and $\forall i(G_i$ has and only one parent graph is $G$)..

(2) $R$ is a set of relations of $G$, where $R \subseteq (N \cup G) \times C$.

ENG is denoted as $G = (N, R)$, according to the Definition2, where $N$, $R$ are the set of graphs in $C$ and the set of relations of $C$ respectively. Unlike the NG, ENG has the ability to represent relations among different layers, such as the relations between places and regions. The uppermost node *root* in ENG as shown in Fig.1, servers as a container for spatial entities. The root node does not have the meaning of spatial object itself, and the relationship between it and other graphs is possession, which is not the subordinate relationship in the spatial sense. ENG based REKModel has an important property: scalability. The scale of REKModel can be increased by inserting a new node or decreased by deleting node.

### *2.2 A Regionalized Spatial Knowledge with Topological and Directional Relations*

In this paper, a method of regionalized spatial knowledge description based on the combination of topological relation and directional relation is proposed. Each description primitive is written as follows “$xTR_{DR}y$”, where $TR$ indicates a mereotopological relation and subscript $DR$ denotes a direction relation. $TR_{DR}$ expresses a combinational description of the two preceding relations. For example, $cD_{E:NE}a$ denotes that “$c$ lies to the east partly and north-east partly of $a$”. In this paper, five kinds of mereotopological spatial relations are considered.

**Definition3** The set $QSKR\_6$ including 5 mereotopological spatial relations and unknown relation is denoted as follows:

$$QSKR\_6 = \{P, IP, O, D, T, \varnothing\}$$

Where primitive relation “P” from mereotopology(Smith (1996)) can describe a kind of inclusion knowledge. The atomic formula $xPy$ denote that “$x$ is part of $y$” as the primitive binary relation of mereotopological theory. A primitive relation derived from $P$ is that $xIPy$ which denote “$x$ is an interior part of $y$”. Then three further primitive relations can be defined. The first primitive relation is that “$x$ overlaps $y$”, denoted $xOy := \exists z(zPx \wedge zPy)$. The second primitive relation is that “$x$ is discrete from $y$” and is described as $xDy := \neg xOy$. More detailed description of the mereotopology can be found in(Smith (1996)).

Direction relation is an important property for spatial reasoning and navigation system. In order to represent internal and external direction relations between two regions, the minimum bounding rectangle(MBR) model(Skiadopoulos and Koubarakis (2004),Papadias et al. (1995)) is used. The MBR of a region is divided into 9 partitions and correspondingly produce 10 primitive relations denoted by $N$ (north), $NE$ (north-east), $E$ (east), $SE$ (south-east), $S$ (south), $SW$ (south-west), $W$ (west), $NW$ (north-west), $M$ (middle), $\varnothing$ (unknown).

**Definition4** The set including all regional direction relations is denoted by $RDR\_10$.

$$RDR\_10 = \{N, NE, E, SE, S, SW, W, NW, M, \varnothing\}$$

**Definition5** $dir(x, y)$ is a function used to represent the $RDR\_10$ relation between the primary $x$ and the reference $y$. i.e. $dir(x, y) = M \equiv xMy$.

Obviously, $dir(x, y) \in RDR\_10$

The composition relations can be deduced via TABLE 1. For instance, we define several refinements of the north relation:

$$xP_Ny := \forall z(zOx \rightarrow zOy) \wedge dir(x, y) = N$$
$$xO_Ny := \exists z(zPx \wedge zPy) \wedge dir(x, y) = N$$
$$xD_Ny := \neg xOy \wedge dir(x, y) = N$$
$$xT_Ny := \exists z(zPx \wedge zBy) \wedge dir(x, y) = N$$

According to previous definitions, "bookshelf is in the west of workroom, and lies to the north west of worktable" can be described as "$bookshelf P_W workroom$, $bookshelf D_{NW} worktable$".

Table 1. Composition table of QSKR_6 and RDR_10 to get qualitative spatial knowledge relations (QSKR_57). ∅: Impossible to happen this relation or unknown relation

| | $P$ | $IP$ | $O$ | $D$ | $T$ | $\varnothing$ |
|---|---|---|---|---|---|---|
| $N$ | $P_N$ | $IP_N$ | $O_N$ | $D_N$ | $T_N$ | $N$ |
| $NE$ | $P_{NE}$ | $IP_{NE}$ | $O_{NE}$ | $D_{NE}$ | $T_{NE}$ | $NE$ |
| $E$ | $P_E$ | $IP_E$ | $O_E$ | $D_E$ | $T_E$ | $E$ |
| $SE$ | $P_{SE}$ | $IP_{SE}$ | $O_{SE}$ | $D_{SE}$ | $T_{SE}$ | $SE$ |
| $S$ | $P_S$ | $IP_S$ | $O_S$ | $D_S$ | $T_S$ | $S$ |
| $SW$ | $P_{SW}$ | $IP_{SW}$ | $O_{SW}$ | $D_{SW}$ | $T_{SW}$ | $SW$ |
| $W$ | $P_W$ | $IP_W$ | $O_W$ | $D_W$ | $T_W$ | $W$ |
| $NW$ | $P_{NW}$ | $IP_{NW}$ | $O_{NW}$ | $D_{NW}$ | $T_{NW}$ | $NW$ |
| $M$ | $P_M$ | $IP_M$ | $\varnothing$ | $\varnothing$ | $\varnothing$ | $M$ |
| $\varnothing$ | $P$ | $IP$ | $O$ | $D$ | $T$ | $\varnothing$ |
| | QSKR_IN_20 | | QSKR_O_10 | QSKR_To_10 | QSKR_On_10 | RDR_10 |
| | QSKR_57 | | | | | |

## 3. MOBILE ROBOT NAVIGATION BASED ON THE REKMODEL

Previous sections focus on representation of regionalized spatial environments. The following section integrates this into a robot navigation system.

### 3.1 A Robot Navigation System Using Memory Models

*Navigation System Framework* In cognitive psychology, spatial memory was proposed to store and recover the spatial and navigation information. Spatial memory stores information at different levels, including working memory, short-term memory and long-term memory. As shown in Fig. 2, the regionlized knowledge of the environment described using the REKModel is stored in Long-Term Memory (LTM). Based on REKModel, the path planner plans a fine-to-coarse route to the destination, and the path information is temporarily stored in the short-term memory (STM), the target generator can obtain the path to generate the next closest goal, guide the robot to move to the closest goal, and finally move to the destination. A navigation system based on memory models with REKModel is illustrated in Fig. 2. Several primary modules consisted in the navigation system are listed below:

- Spatial Memory. Store, recall and process information about the spatial environment.
- Fine-to-Coarse pathfinder. Find a "fine-to-coarse" route from current location to destination.
- Closest Goal Generator and Execution. It builds a bridge between the path planner and the robot's movement behavior, and makes the robot move according to the planned path.
- I AM HERE. Maintain the context information of current location.

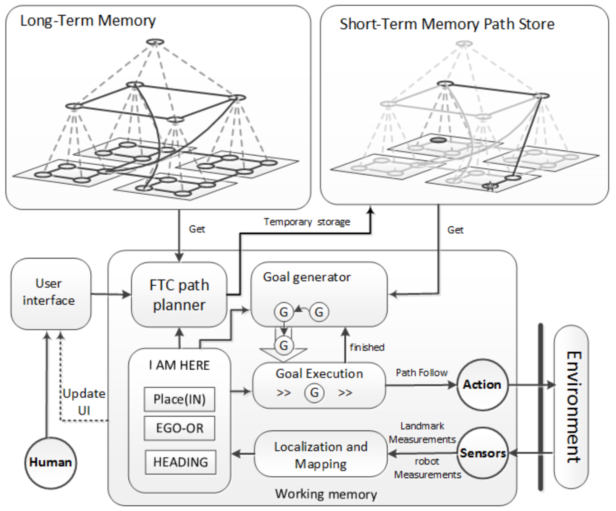


Fig. 2. A schematic diagram of the navigation system. The robot receives the target command from the user, and then the path planner finds a "fine-to-coarse" route to guide the robot to the destination step by step.

*I AM HERE* Agent's location can be described in the form of qualitative relations with respect to other objects, e.g. "I am in the center of Times Square". In the case of describing the relations to ourselves, intrinsic or egocentric reference frame, such as "The notebook is in front of me", usually be used. Driving car strongly relies on purely egocentric view. Reference(Kozhevnikov et al. (2006)) pointed out that the navigation task involves representing, updating, and using self-to-object (egocentric) representations. The egocentric reference frame and the corresponding ego orientation model(Shi and Krieg-Brückner (2008)) with distinguish eight directions are shown in Fig.3.

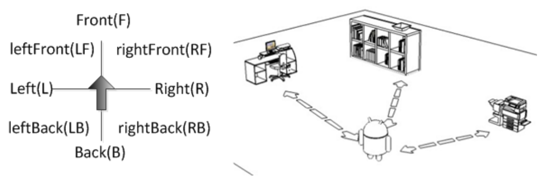


Fig. 3. Egocentric reference frame. The thick arrow denotes the intrinsic front of an agent. Egocentric reference system represents the location of objects in space relative to the body-self (left-right, front-back, and up-down).

In this paper, The function module in Fig.3 which maintains the current position is called as "I AM HERE" and defined as:

I AM HERE:

PLACE :$\{iRregion\}$ $R \in QSKR\_IN\_20$

EGO-OR :$\{(r_1, object_1, i), \cdots\}$

HEADING :{ 2-D orientation}

PLACE denotes where I am in. EGO-OR describes our noticed objects around us and these relations with us, e.g. "the desk is in left of me". HEADING which can be seen as an internal compass represents the global orientation of the agent's head. HEADING is similar to head direction cells. As a consequence, "I AM HERE" status need to be updated as the agent moves.

*"Fine-to-Coarse" Route and its Planning Algorithm* The fine-to-coarse pathfinding strategy uses fine path description for the current location and coarse path information (usually regional connection) for the distant location. In this path representation, a path segment may be described as place-place, place-region or region-region and include directional relation, such path is shown in STM of Fig. 2. The detailed plan for the current environment around the robot allow for immediate motion planning. The route plan must to be updated over time and the robot always has a detailed plan for movement decisions along the route. And the"fine-to-coarse" path planning algorithm is described as Algorithm 1.

Line 10 reflects that if current best node $n_c$ is destination $n_d$ or $n_d$ is in the region $n_c$, we think the algorithm find the "fine-to-coarse" path. Line 19 has two conditions must be met. They are the previous node of current best node $n_c$ is not null and the neighbor node of $n_c$ and the node $n_c$ aren't in the same region of next layer. The robot is likely to change its destination halfway. The path planning algorithm takes the current position as the starting point, updates the target point, and re-plans the path, so it is easy to achieve this change.

*The Closest Goal Generation and Path Following* The goal generator enables the robot to decide what the next closest goal is. There is an active process that monitors the status of "I AM HERE" and generates the next target task for the robot. While the goal is reached, the goal generator generates another next goal to execute the goal until the final goal is reached. The target generator can delete previous targets and generate new targets when new instructions are generated.

## 4. EXPERIMENTS AND RESULTS

As described before, the aim of the experiment was to validate the regional spatial representation and its application to "fine-to-coarse" pathfinding strategy. This experiment was run on Pioneer SDK from Adept MobileRobots LLC. MobileSim is a mobile robot simulation software. ARI Anetwork Server encapsulates MobileSim and provides the interface for remote access and control of the robot. Mobile robot client written in Java is a remote connection to the ARIA Network Server library, providing a user interface. At the top of the software architecture, the navigation module is the core of the whole system, which is built on the NetBeans rich client platform and Java SE 8. The module has a graphical user interface, which is used to view the movement of the robot and the state of the sensor, and send action instructions to the robot.

**Algorithm 1** The fine-to-coarse pathfinding algorithm

**Input:**
The Extended Nested Graph, $G = (N, R)$;
The source node, $n_s$;
The destination node, $n_d$;
**Output:**
The node list of best "fine-to-coarse" path, $ftcPath$;
1: {Initialize the pathfinder}:
2: Path_Set $Open\_List = \{n_s\}$, $Closed\_List = NULL$;
3: Node $n_c = NULL$, $n_s.cost = 0$;
4: {Initialization complete.}
5: **while** $Open\_List$ is not empty **do**
6: $n_c = GET\_BEST\_NODE(Open\_List)$;
7: **if** $n_c$ is $NULL$ **then**
8: **return** as failure;
9: **end if**
10: **if** $n_c$ is $n_d$ or $n_d P n_c$ **then**
11: construct path and save it in $ftcPath$;
12: **return** $ftcPath$;
13: **end if**
14: **for** each neighbor $node$ of $n_c$ **do**
15: Node $n_{pre} = n_c.previousNode$;
16: **if** $node$ is $n_{pre}$ **then**
17: continue;
18: **end if**
19: **if** $n_{pre} \neq NULL$ and $n_{up1} \neq n_{up2}$ where $nodePn_{up1}$, $n_c Pn_{up2}$ **then**
20: set $node = n_{up1}$;
21: **end if**
22: **if** $node$ is in $Closed\_List$ **then**
23: continue;
24: **end if**
25: set boolean $isInOpen = false$;
26: set Node $n_o = CHECK(Open\_List, node)$
27: **if** $n_o \neq NULL$ **then**
28: set $node = n_o$;
29: set $isInOpen = true$;
30: **end if**
31: set $nodeCost = n_c.cost + Cost(n_c, node)$
32: **if** $isInOpen$ is $true$ and $nodeCost \geq n_o.cost$ **then**
33: continue;
34: **end if**
35: **if** $isInOpen$ is $true$ **then**
36: remove node from $Open\_List$;
37: **end if**
38: set $node.previousNode = n_c$;
39: set $node.cost = nodeCost$;
40: set $node.heuristic = Heuristic(node, n_d)$;
41: set $node.value = node.cost + node.heuristic$;
42: add $node$ to $Open\_List$;
43: sort the $Open\_List$ ;
44: **end for**
45: **end while**

### *4.1 The Virtual Environment*

A regionalized virtual environment was created, consisting of four regions, each with four places, for a total of 16 places, as shown in Fig.4(a). These places are connected by roads 10 meters long. The spatial knowledge of the environment, organized by REKModel, is pre stored in the robot's LTM. Fig.4(b) shows a storage structure of the spatial knowledge expect for the thick lines of fine-to-coarse route. Each connection between two places was expressed by qualitative information, see TABLE 2 for detailed descriptions.

Table 2. Qualitative relationships between nodes of regionalized environments. ∅: unknown or unset relation

| | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $n_5$ | $n_6$ | $n_7$ | $n_8$ | $n_9$ | $n_{10}$ | $n_{11}$ | $n_{12}$ | $n_{13}$ | $n_{14}$ | $n_{15}$ | $n_{16}$ | $n_{17}$ | $n_{18}$ | $n_{19}$ | $n_{20}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $n_1$ | ∅ | $D_W$ | $D_N$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{NW}$ | ∅ | ∅ | ∅ |
| $n_2$ | $D_E$ | ∅ | ∅ | $D_N$ | $D_W$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{NE}$ | ∅ | ∅ | ∅ |
| $n_3$ | $D_S$ | ∅ | ∅ | $D_W$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{SW}$ | ∅ | ∅ | ∅ |
| $n_4$ | ∅ | $D_S$ | $D_W$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_N$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{SE}$ | ∅ | ∅ | ∅ |
| $n_5$ | ∅ | $D_E$ | ∅ | ∅ | ∅ | $D_W$ | $D_N$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{NW}$ | ∅ | ∅ |
| $n_6$ | ∅ | ∅ | ∅ | ∅ | $D_E$ | ∅ | ∅ | $D_N$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{NE}$ | ∅ | ∅ |
| $n_7$ | ∅ | ∅ | ∅ | ∅ | $D_S$ | ∅ | ∅ | $D_W$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{SW}$ | ∅ | ∅ |
| $n_8$ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | $D_E$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_N$ | ∅ | ∅ | ∅ | $P_{SE}$ | ∅ | ∅ |
| $n_9$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_W$ | $D_N$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{NW}$ | ∅ |
| $n_{10}$ | ∅ | ∅ | ∅ | $D_S$ | ∅ | ∅ | ∅ | ∅ | $D_E$ | ∅ | ∅ | $D_N$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{NE}$ | ∅ |
| $n_{11}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | ∅ | ∅ | $D_W$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{SW}$ | ∅ |
| $n_{12}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | $D_E$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $P_{SE}$ | ∅ |
| $n_{13}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_E$ | ∅ | ∅ | ∅ | $D_W$ | $D_N$ | ∅ | ∅ | ∅ | ∅ | $P_{NW}$ |
| $n_{14}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | ∅ | ∅ | ∅ | ∅ | $D_E$ | ∅ | ∅ | $D_N$ | ∅ | ∅ | ∅ | $P_{NE}$ |
| $n_{15}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | ∅ | ∅ | $D_W$ | ∅ | ∅ | ∅ | $P_{SW}$ |
| $n_{16}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | $D_E$ | ∅ | ∅ | ∅ | ∅ | $P_{SE}$ |
| $n_{17}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_W$ | $D_N$ | ∅ |
| $n_{18}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_E$ | ∅ | ∅ | $D_N$ |
| $n_{19}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | ∅ | ∅ | $D_W$ |
| $n_{20}$ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | ∅ | $D_S$ | $D_E$ | ∅ |

### *4.2 Process and Results*

The robot needs to move from a given starting point to a single target point. Fig. 4(b)-(g) shows the entire process of this task. Before the robot starts to navigate, "I AM HERE" status and route towards destination should be initialized as:

I AM HERE:

PLACE :$\{iPn_{19}\}$

EGO-OR :$\{(L, n_9, i)\}$

HEADING :$\{E\}$

This state indicates that I am in the region $n_{19}$, the place $n_9$ lies to left of me, and I face east. The route path is planned by using the fine-to-coarse pathfinding algorithm. At this time, Fig.4(b) represents the initial

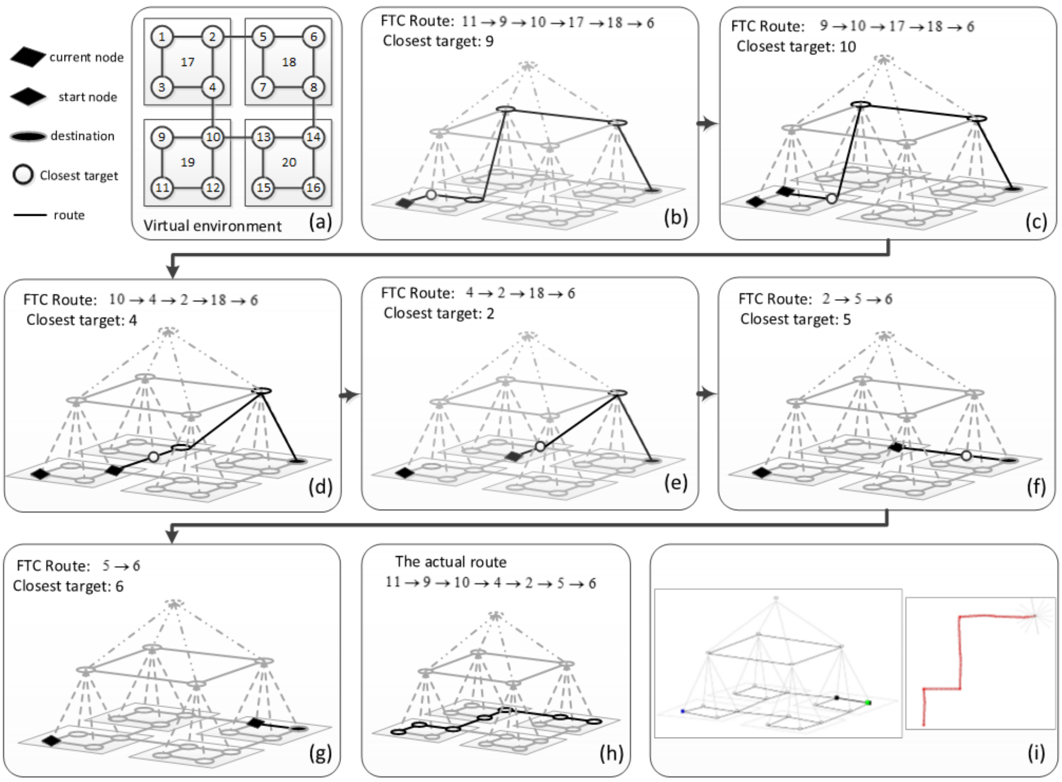


Fig. 4. Mobile robot navigation in a regionalized environment. (a) A regionalized virtual environment. Places are displayed as numbered circles. Roads are represented by lines. The rectangles represent the region. (b)-(g) The process of robot navigation from place $n_{11}$ to place $n_6$. The "fine-to-coarse" route was found by using pathfinding algorithm. (h) The actual path the robot followed. (i) The views of navigation results in navigation system GUI and MobileSim, respectively.

route: 11 → 9 → 10 → 17 → 18 → 6. According to the route, the closest target $n_9$ was generated and the goal executor worked until reach the goal. Due to the closest goal $n_9$ was to the left of the robot, a turn left behavior was triggered until the robot faced it and then moved to it.

Once the task starts, the "I AM HERE" status is updated over time to reflect the results of the robot's movement. When the robot reaches position $n_9$, it replans the route to the destination, generates a new closest target $n_{10}$ and guides the robot to continue its movement. Repeat this process until all goals in path was reached. Fig.4(h) shows the actual route followed by robot. Fig.4(i) views the process of navigation in navigation system GUI and MobileSim, respectively.

The simulation reveals the operation process of navigation based on regionalized spatial knowledge. Under the guidance of a sub-target, the robot guides the robot to move towards the target until the final destination. The reasoning of its motion behavior is consistent with the description of the path and the cognitive habits of people to find and guide the way, which can enhance the ability of navigation system to adapt to the environment and human-computer interaction.

## 5. CONCLUSION

In this paper, a hierarchical and regional environmental knowledge model (REKModel) and a mobile robot navigation system based on fine-to-coarse pathfinding strategy are constructed. REKModel simulates the expression of natural environment in the human brain, regionalizes the environment, and the upper level region contains the lower level region, forming a nested iterative organizational structure. A computable data model-ENG is used to organize and describe REKModel. REKModel is a simple, universal and extensible environment knowledge description model. REK model is stored in the navigation system as prior knowledge of the environment. FTC pathfinding algorithm uses the environmental knowledge to dynamically plan the fine-to-coarse path from the current position of the robot to the target online. The planning algorithm reduces the memory load and computational complexity by planning the path of the robot's surrounding environment precisely and planning the path of the robot's distance coarsely, which also makes the robot have the ability to plan the next movement behavior in real time, and guides the robot to move step by step to the final goal. The simulation results show that the navigation system is effective and feasible.

## REFERENCES

Boccia, M., Nemmi, F., and Guariglia, C. (2014). Neuropsychology of environmental navigation in humans: review and meta-analysis of fmri studies in healthy participants. *Neuropsychology review*, 24(2), 236–251.

Gallistel, C. and Cramer, A.E. (1996). Computations on metric maps in mammals: getting oriented and choosing a multi-destination route. *Journal of experimental biology*, 199(1), 211–217.

Gopal, S., Klatzky, R.L., and Smith, T.R. (1989). Navigator: A psychologically based model of environmental learning through navigation. *Journal of environmental Psychology*, 9(4), 309–331.

Kostavelis, I. and Gasteratos, A. (2015). Semantic mapping for mobile robotics tasks: A survey. *Robotics and Autonomous Systems*, 66, 86–103.

Kozhevnikov, M., Motes, M.A., Rasch, B., and Blajenkova, O. (2006). Perspective-taking vs. mental rotation transformations and how they predict spatial navigation performance. *Applied Cognitive Psychology*, 20(3), 397–417.

Kuric, I., Bulej, V., Saga, M., and Pokorny, P. (2017). Development of simulation software for mobile robot path planning within multilayer map system based on metric and topological maps. *International journal of advanced robotic systems*, 14(6), 1729881417743029.

O'Neill, M.J. (1992). Effects of familiarity and plan complexity on wayfinding in simulated buildings. *Journal of Environmental Psychology*, 12(4), 319–327.

Papadias, D., Sellis, T., Theodoridis, Y., and Egenhofer, M.J. (1995). *Topological relations in the world of minimum bounding rectangles: A study with R-trees*, volume 24. ACM.

Shi, H. and Krieg-Brückner, B. (2008). Modelling route instructions for robust human-robot interaction on navigation tasks. *International Journal of Software and Informatics*, 2(1), 33–60.

Skiadopoulos, S. and Koubarakis, M. (2004). Composing cardinal direction relations. *Artificial Intelligence*, 152(2), 143–171.

Smith, B. (1996). Mereotopology: a theory of parts and boundaries. *Data & Knowledge Engineering*, 20(3), 287–303.

Spiers, H.J. and Maguire, E.A. (2008). The dynamic nature of cognition during wayfinding. *Journal of environmental psychology*, 28(3), 232–249.

Voicu, H. (2003). Hierarchical cognitive maps. *Neural Networks*, 16(5-6), 569–576.

Wiener, J.M. and Mallot, H.A. (2003). 'fine-to-coarse'route planning and navigation in regionalized environments. *Spatial Cognition and Computation*, 3(4), 331–358.

Wiener, J.M., Schnee, A., and Mallot, H.A. (2004). Use and interaction of navigation strategies in regionalized environments. *Journal of Environmental Psychology*, 24(4), 475–493.