A Conceptual Model for Human-Robot Collaborative Spatial Navigation

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Abstract

This paper describes our work on developing effective, efficient and user-friendly interaction between a human operator and a mobile robot on performing spatial navigation tasks. In order to solve the spatially related communication problems caused by the disparity between human mental representation about spatial environments and that of a mobile robot, a qualitative spatial knowledge based four-level conceptual model is proposed. With a computational framework based on an application dependent instance of this model, high-level conceptual strategies are implemented and used to support the human-robot collaborative spatial navigation. An empirical study is then conducted to evaluate the computational framework implemented into a practical interactive system using a real environment map regarding different conceptual strategies.

Keywords: Conceptual Modelling, Qualitative Spatial Representation and Reasoning, Communication of Spatial Information, Human-Robot Interaction.

1 Introduction

As intelligent service robots are receiving more and more attention in academic and industrial areas, considerable research efforts have been dedicated to the development of effective, efficient and user-friendly human-robot interaction in different application domains (Fong et al (2003), Goodrich and Schultz (2007)). The major concern of our work is placed on solving communication problems during human-robot interaction in the domain of spatial navigation, where a mobile service robot is collaboratively controlled by an intelligent embedded system for low-level autonomous navigation and a human operator for giving high-level conceptual route instructions using natural language. The human operator can tell the robot, for example, to turn around, go straight ahead, take a right, and then pass a coffee machine on the left, until it reaches the copy room.

Much research has been devoted in this area, e.g., (Koulouri and Lauria 2009) and (Shi and Tenbrink 2009) performed corpus-based analysis on natural language route directions with mobile robots; (Kollar, et al 2010) and (Marge and Rudnicky 2010) studied the relationship between features of spatial environment and language, especially the role of natural language in route instructions; (Zender, et al 2008) and (Mozos 2010) proposed and improved a multi-layered conceptual model corresponding to spatial and functional properties of typical indoor environments based on topological information, then used this model to support a mobile robot's indoor navigation. Diverging from these methods and models concentrating on empirical data, natural language and topological conceptual information, our work is focusing on human perspectives according to the following two important aspects.

First, in human-robot collaborative navigation, human operators usually use natural language expressions containing qualitative relations and conceptual landmarks (Hirtle 2008), such as "go to the end of the corridor, turn right, and then go until the coffee machine on the left", while mobile robots work on quantitative level and can only interpret instructions with quantitative data, such as "145.0 meters ahead, then make a 37.5 degree turning, …". There is apparently a gap between a human operator and a mobile robot if they want to communicate with each other. Much research has been focusing on applying mathematical well-founded qualitative spatial calculi and models to represent and reason about spatial environments (e.g. Ligozat and Renz (2004), Schultz, et al (2006), Wolter and Lee (2010), Kurfess, et al (2011)). Adding to this body of literature, using qualitative spatial knowledge as an intermediate layer for the intuitive human-robot communication has been viewed as the foundation of our work.

Furthermore, providing a sequence of route instructions is a rather complex process for the human operator, since spatially-related communication problems could easily occur if spatial objects are wrongly localized or a certain instruction is wrongly given due to a certain spatial situation, e.g., a coffee machine cannot be found after taking a right turn, or a room to be passed is not on the left as expected (Reason (1990) and Bugmann (2004)). Therefore, an effective mechanism is needed for the mobile robot and the human operator to collaboratively identify the problems and negotiate possible solutions with each other.

Thus, in order to bridge the interaction gap between the human operator's qualitative spatial mental model and the mobile robot's quantitative representation, as well as supporting the high-level collaborative negotiation of spatially-related communication problems, we proposed a qualitative spatial knowledge based four-level conceptual model: the Qualitative Spatial Beliefs Model (QSBM). This model was first proposed in (Shi and Krieg-Brückner 2008), and then extended and implemented with a computational framework (Jian, et al 2009) and a set of high-level conceptual strategies to support collaborative human-robot spatial navigation (Shi, et al 2010). Two conceptual strategies were evaluated and compared in (Jian, et al 2010). With the further development of the conceptual model based computational framework and the integration into a practical interactive system for a mobile robot, the current paper reports on a new high-level conceptual strategy for resolving more spatially-related human-robot communication problems, as well as an empirical study, which was conducted to test the current system with the focus of evaluating the new conceptual strategy and its comparison with the previous strategies.

The remainder of the paper is organized as follows. Section 2 presents the qualitative spatial knowledge based four-level conceptual model and one of its application dependent instance with conceptual strategies to solve the spatially related communication problems. Section 3 introduces the computational framework that implements the conceptual model. Section 4 then describes the empirical study to evaluate a practical interactive system regarding the model-based conceptual strategies and Section 5 discusses the results of the study. Finally, Section 6 concludes the paper and gives an outline to our future work.

2 A Qualitative Spatial Knowledge based Four-Level Conceptual Model

2.1 The Overview of the General Model

According to the perspective of human operators, spatial environments are not represented with quantitative data as a mobile robot does, but with conceptual objects or places and their qualitative spatial relations. Accordingly, Qualitative Spatial Beliefs Model (QSBM), a qualitative spatial knowledge based conceptual model is developed to model a mobile robot's beliefs for supporting more intuitive communication with human operators. Figure 1 illustrates the general QSBM with a four-level structure.

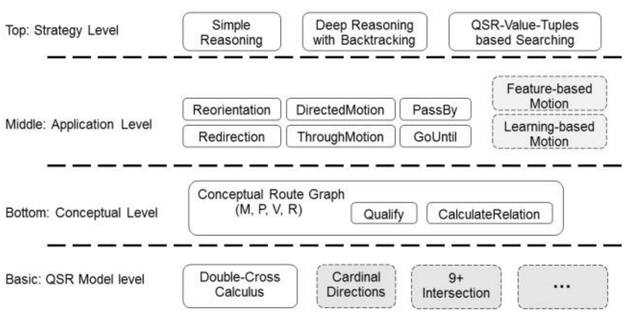

Figure 1: The QSR-based four-level conceptual model: Qualitative Spatial Beliefs Model (QSBM)

The basic level is the QSR Model level, which contains the most basic theoretical foundation of the QSBM model: qualitative spatial calculi for different application requirements, such as Double-Cross Calculus (Freksa, 1992), Cardinal Directions (Frank, 1991), 9+ Intersection (Kurata, 2008), etc.

Based on the chosen qualitative spatial calculus, a basic conceptual model can be constructed and serves as the fundamental conceptual level. This level only contains qualitative spatial information and the basic calculating and reasoning mechanism with respect to the connection between the chosen calculus and the navigation environment. It can be seen as a black box holding a conceptual qualitative spatial knowledge based representation of a spatial environment with two basic functions: *Qualify* for qualifying quantitative information into qualitative relations, and *CalculateRelation* for calculating additional qualitative spatial relations with qualitative spatial relations between objects using calculus-based qualitative spatial reasoning.

The application level consists of a set of most atomic application-dependent update rules, which correspond to all the possible user-uttered route instructions to a mobile robot in collaborative spatial navigation. For instance, the update rule *Reorientation* can refer to the instruction "turn left", *Redirection* can interpret "take the next junction on the left". *Feature-based Motion* concerns instructions with features of objects or landmarks, such as "go around the big laboratory" (see (Gondorf and Jian, 2011)), and *Learning-based Motion* represents those instructions requiring the robot to augment its conceptual knowledge by learning new landmarks or disambiguating landmarks, such as "the third office is the directory's office, pass by it", etc. Each update rule is used to update the state of the spatial representation on the conceptual level with respect to its formal definition based on a chosen calculus and the related qualitative spatial reasoning on the QSR Model level.

On the strategy level, high-level conceptual strategies are developed to assist in interpreting a sequence of route instructions and if possible, resolve the spatially-related communication problems during the collaborative spatial navigation. Basically, each conceptual strategy defines its own mechanism for appropriately choosing and applying atomic update rules on the application level.

In general, the QSBM is a conceptual model for applying qualitative spatial knowledge to represent a spatial environment, qualitative spatial reasoning to define a set of application-dependent update rules to update the conceptual representation, and conceptual strategies to manage the atomic update rules to support high-level spatially-related human-robot communication. With the flexibility and expandability provided by the multi-level structure, further application scenarios can be supported by using different qualitative calculi on the QSR model level, more application-dependent actions can also be added on the application level, or new high-level strategies can also be implemented to resolve more communication problems, while each of these changes/extensions requires only limited adaptation on the other levels in QSBM.

Specifically, since qualitative spatial calculi at the QSR Model Level are well studied, formal details about the other three levels of an instance of QSBM will be given in the rest of the chapter.

2.2 A DCC-based QSBM

Considering the current requirement of the collaborative spatial navigation scenarios, double-cross calculus (DCC) is selected as the basic QSR model and a DCC-based

QSBM is developed (Shi, et al 2010) and introduced according to the conceptual, application and strategy level as follows.

2.2.1 The Conceptual Level

In mobile robot navigation, one of the most important basic models is called Route Graph (Werner, et al 2000). Route graphs are a special class of graphs, with graph nodes representing conceptual places at geographical positions regarding a quantitative reference system, and graph edges or route segments, each of which is directed from one node to another and altogether build up a conceptual network of routes (see Fig. 2 a)). Conventional route graphs cannot only be used as quantitative representation of spatial environments for mobile robots' navigation, they also capture the topological knowledge of space from human perspective and therefore have the potential of intermediate layers for human operators. However, the gap between quantitative representation of conventional route graphs and qualitative knowledge based mental construct of human operators remains a problem preventing a more direct interaction.

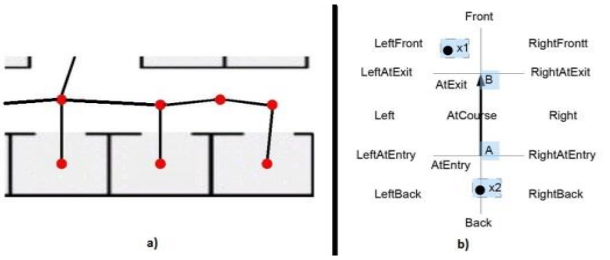

Figure 2: a) one part of a conventional route graph; b) the orientation frame of Double Cross Calculus with 15 qualitative spatial relations.

On the other hand, Double Cross Calculus (DCC (Freksa, 1992)) divides the 2-dimensional space with a directed segment into disjoint grids (see Fig. 2 b)), which defines 15 meaningful qualitative spatial relations. Thus, a DCC model can be used as a local navigation map from an egocentric perspective and support the interaction with human operators in a local navigation scenario.

By combining the structure of a conventional route graph and the DCC model, the conceptual route graph (CRG) is developed (Shi and Krieg-Brückner, 2008). A CRG inherits the topological structure from a conventional route graph, where quantitative information is completely replaced by the DCC relations between graph nodes and route segments. Formally, a CRG of a spatial environment is defined by a tuple of four elements (M, P, V, R):

- M is a set of landmark-place-pairs in the environment, specifying the locations of all the landmarks at places in P, such as an {office: x_1}, or a {kitchen: x_2}.
- P is a set of topological places, or the graph node in a CRG, such as x_1 or x_2.
- V is a set of vectors, each of which is directed from one place to another place, such as *AB*.
- R is a set of relation-pairs, which specify the DCC relations between places and vectors. A relation pair is written as <AB, LeftFront, x_1>, meaning that x_1 is in the LeftFront grid of AB.

Therefore, the CRG for the simple spatial environment illustrated in Fig. 2 b) is represented as:

```
crg = (M = {office:x1,kitchen:x2},
       P = {A, B, x1, x2},
       V = {AB, BA},
       R = {<AB, LeftFront, x1>, <AB, Back, x2>})
```

And a state of a DCC-based QSBM model, which is stored as a mobile robot's internal representation about current spatial situation, can then be represented for example as:

```
       <crg, pos = AB>
```

This means that the mobile robot is now located at place A and looking at the direction of place B, with an office on the LeftFront position and kitchen at the Back.

2.2.2 The Application Level

In order to support the application scenarios of human-robot collaborative spatial navigation, a set of route instructions such as "turn left", "take the next junction on the right", "pass by the office on the left", etc., should be interpreted by the mobile robot. According to the formal definition of the DCC-based CRG on the conceptual level, a set of low-level update rules regarding the most common route instructions for mobile robots are developed on the application level and used to update the state of the DCC-based QSBM, i.e., the state of a mobile robot about spatial environment.

Each update rule is specified with the following three elements:

- a name (followed by RULE), which identifies a class of most common route instructions,
- a set of preconditions (followed by PRE), under which this update rule can be applied, and
- an effect (followed by EFF), describing how the state of the DCC-based QSBM is updated after applying the update rule.

As examples, the update rules for reorientation and directed motion are presented as follows:

- **Reorientation** refers to the simplest route instructions, which change the current orientation of a robot, such as "Turn left", "Turn right" and "Turn around". In general, the precondition is whether a robot can find a CRG vector satisfying two conditions: 1. it is originated from the current place and 2. It is targeted at a place that has the desired spatial relation with the current position; the effect is that the robot position is updated as that found CRG vector, formally described as:

```
RULE: Reorientation
PRE: pos = P0P1,
     ∃P0P2∈V. <P0P1, dir, P2>
EFF: pos = P0P2
```

Concretely, the rules indicates that the robot is currently at the place P_0 and faces the place P_1 (P_0P_1 is a CRG vector), if there exists a CRG vector P_0P_2 with a targeting place P_2, such that the spatial relation of P_2 with respect to the route segment P_0P_1 (i.e. the current position) is the desired direction dir to turn, i.e., $\langle P_0P_1$, dir, $P_2\rangle$, then the current position will be updated as P_0P_2 after applying this update rule.

- **Directed Motion** defines the class of the route instructions that usually contain a motion action and a turning action changing the direction of the continuing motion, such as "take the next junction on the right". These instructions usually involve with a landmark (e.g. the "junction"), until which the robot should go, and a direction (e.g. on the "right"), towards which the robot should turn. For example, in general, for the route instruction "take the next corridor on the right", the first corridor on the right from the robot's current position needs to be identified first. Thus, the update rule for directed motions with the first landmark and a turning direction is specified as:

RULE: DirectedMotionWithFstLandmarkAndDir
PRE: pos = P_0P_1,
$\exists P_2P_3 \in V.\ ((l{:}P_2) \wedge \langle P_1P_2, dir, P_3\rangle \wedge \langle P_0P_1, Front, P_2\rangle)$
$\wedge \forall P_4P_5 \in V.\ ((l{:}P_4) \wedge \langle P_1P_4, dir, P_5\rangle \wedge \langle P_0P_1, Front, P_4\rangle$
$\wedge\ (P_2 \neq P_4)) \rightarrow \langle P_1P_2, Front, P_4\rangle$
EFF: pos = P_2P_3

In this rule, l is the targeted landmark and dir is the direction to turn to; The first precondition specifies that the robot should find a CRG vector P_2P_3, such that the targeted landmark is located at P_2, the spatial relation between P_3 and the segment P_1P_2 is the desired direction dir and P_2 is in front of the robot's current position; The second precondition limits that P_2 is the first place referring to the given landmark at the given direction, instead of an arbitrary one; this condition is satisfied if there exists a place P_4 with the same feature as P_2, P_4 must be ahead of P_2 from the current perspective. The effect is that, the robot position is updated to P_2P_3 after applying this rule. Similarly, other variants of directed motions, such as "go straight ahead", "go right" or "take the second left" can be specified with similar update rules accordingly.

2.2.3 The Strategy level

With the update rules defined on the application level, single route instructions can be interpreted. However, in human robot collaborative navigation, human operators usually give a sequence of route instructions to the mobile robot. In this case, if a certain route instruction is wrongly given, spatially related communication problems could easily occur, because taking the wrong route instruction could cause problems of interpretation of the subsequent route instructions, which could result in failure of the entire interpretation or even lead to a completely unexpected route.

In order to resolve these problems, a set of high-level conceptual strategies are developed on the strategy level, which apply the low-level update rules accordingly and appropriately according to different principles and methods. Among them, the two most important conceptual strategies are briefly introduced as follows.

2.2.4 Reasoning with Backtracking

With the qualitative spatial reasoning on the QSR model level, the preconditions of update rules on the application level can easily be checked, this is in fact the most straightforward way to see if a sequence of route instructions can be interpreted. However, there are often situations where the failure of the interpretation of some instructions is caused by a previously incorrect instruction, e.g. see the situation in Fig. 3. The robot is located at the thick red arrow and the instructions are: "go straight ahead, then go left, and then turn right, and go until the kitchen on the right." A simple check fails on interpreting the fourth instruction "go until kitchen on the right", because there is no kitchen ahead after taking a right turn as the previous instruction. However, by taking one step backwards, if the third instruction is changed from right to left, then the last instruction can also be interpreted properly.

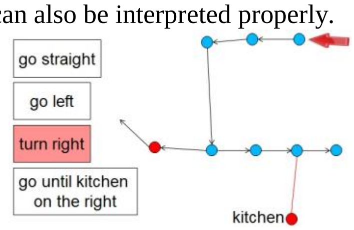

Figure 3: An example of a wrong instruction

Thus, the strategy "Reasoning with Backtracking" (abbr. RwB) interprets the route instructions as the straightforward way does, checking every precondition as usual. Yet after applying each update rule, the state of the updated QSBM is also saved in an interpretation history. Once one instruction cannot be interpreted, the previous state of the QSBM can be reloaded as the current state and possible suggestion can be made based on the previous instruction, such as "turn left" instead of "turn right" in the example in Fig. 3. As a result, the checking of the preconditions of the remaining route instructions can be resumed based on the suggested route instruction, and a possible route matching the entire sequence of route instructions can be found.

The RwB strategy has been evaluated and compared with other conceptual strategies and the positive results were reported in (Jian, et al 2010).

2.2.5 QSR-Value Tuples based Searching

During the development and integration of the QSBM model into an interactive system to be used by a mobile robot, a new class of spatially-related communication problems is identified. Fig. 4 illustrates one example of these problems.

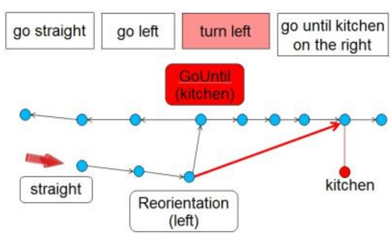

Figure 4: An example of a "missing" instruction

In this example, the robot is located at the thick red arrow and the instructions are "go straight, then left, then go until the kitchen on the right". From the perspective of the human operator, the kitchen is located directly on the right side, and therefore the operator simply ignores a turning point that is in the conceptual representation but not in his/her mental representation. However, after taking a right turn, the last instruction "go until kitchen on the right" cannot be interpreted, because there is no continuing possibility as shown in Fig. 4.

These problems cannot be solved by the RwB strategy, because the RwB strategy can only provide suggestions if there exists a wrong route instruction, while in these situations one route instruction is missing. Thus, the strategy "QSR-Value Tuples based Searching" (abbr. QSRVT) was developed. For each outgoing direction of each turning node in a conceptual route graph during the interpretation, a QSR weighted value tuple is defined as:

```
(route, instructions, qsr_v)
```

where *route* is the currently taken route, *instructions* is the set of all the along this route interpreted instructions, and *qsr_v* is the cumulative value calculated by

$$qsr\_v = \sum_{i=0}^{i_{current}} mr_i * sr_i$$

where mr_i is the matching rate by comparing the desired qualitative spatial direction with the current route direction while interpreting the i-th instruction, sr_i is the success rate of interpreting the i-th route instruction, and $i_{current}$ is the index of the current route instruction.

The QSRVT strategy first initializes an empty set of QSR-value tuples at the starting position of the robot. This set of QSR-value tuples is then automatically updated and expanded by the searching agents of the QSRVT strategy, while they are travelling along all paths (according to the branching of each turning node) in the QSBM. Finally, a full set of QSR-value tuples is generated and the QSR-value tuple with the highest QSR-weighted value is either the best possible solution for interpreting the route instructions or contains the most relevant information to provide possible suggestion to resolve the spatially-related communication problems.

As an example, Fig. 5 briefly illustrates how the QSRVT strategy solves the problem in Fig. 4.

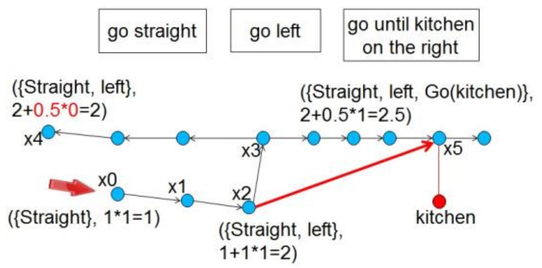

Figure 5: A simple process of the QSRVT strategy

After interpreting the first two instructions "go straight" and "go left", the searching comes to the turning node x3. There are two possible directions going out of x3 and accordingly two more QSR-value tuples are added. In this situation, the last instruction cannot be interpreted with the left going route while it can be interpreted with the right going one. Therefore, the instructions are interpreted with the route x0->x1->x2->x3->x5, since the QSR-value tuple has the highest value 2.5.

3 A Conceptual Model based Computational Framework

Based on the introduced QSBM, including update rules and the high-level conceptual strategies, we developed SimSpace, a conceptual model based computational framework for supporting the implementation of QSBM into a practical interactive system to be used by a mobile robot.

3.1 General Architecture

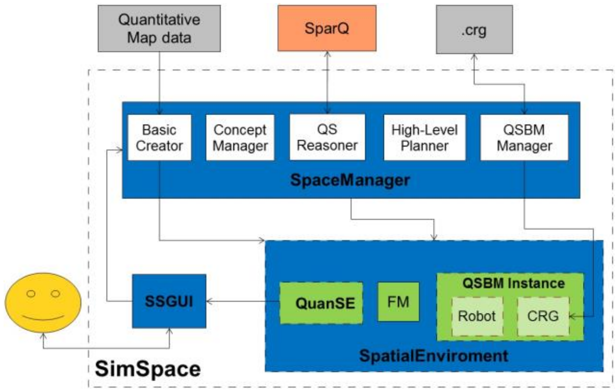

Figure 6: The general architecture of SimSpace

According to the Model-View-Controller architecture (originally from (Burbeck 1987)), the general architecture of SimSpace consists of a Model component *Spatial Envioronment*, an optional View Component *SSGUI* and a Controller *SpaceManager*:

Spatial Environment maintains the current state of the QSBM instance, i.e., the conceptual route graph and the hypothesis of the robot position in the CRG, as well as the optional quantitative spatial environment (QuanSE) for quantitative data and the optional feature map (FM) component containing the conceptual information.

SSGUI is the graphical user interface of SimSpace. It is an optional component and is only used if the SimSpace system is started as a stand-alone application. It visualizes the spatial environment with quantitative and conceptual descriptions, interacts with a human user who is giving the natural language route instructions, and communicates with the Space Manager for the interpretation of incoming route instructions as well as outgoing system responses.

Space Manager is the central processing component of SimSpace, it consists of the following five functional components:

- Basic Creator creates a spatial environment instance with quantitative and conceptual data according to the quantitative map data, if given.
- Concept Manager manages an ontology database of the conceptual knowledge, such as names of landmarks or persons, how they are conceptually related, etc. It is used to interpret the conceptual terms in the natural language route instructions.

- QS Reasoner is connected with SparQ (Wolter and Wallgrün 2011), a general toolbox for qualitative spatial representation and reasoning. It supports the most basic operations on the conceptual level in QSBM, e.g., qualification of quantitative data into qualitative relations and calculation of qualitative spatial relations.
- QSBM Manager connects with QS Reasoner and generates a QSBM instance according to a qualitative spatial calculus on the QSR model level and a quantitative environment if given, manipulates and updates an empty or existing QSBM instance with the application dependent update rules on the application level, and saves the updated QSBM instance into a XML-based specification with .crg file extension, if needed.
- High-Level Planner implements the high-level conceptual strategies to apply appropriate update rules to interpret route instructions and resolve spatially-related communication problems.

3.2 The Interpretation of Route Instructions in SimSpace

The SimSpace system can interpret a sequence of human route instructions in the following steps:

- The sequence of route instructions is firstly parsed into a list of predefined semantic representations.
- According to the activated high-level conceptual strategy, each semantic representation is assigned with an applicable low-level update rule.

  For each low-level update rule, its preconditions are instantiated. Taking the sample instruction "go until the kitchen on the right" in the previous section, the update rule GoUntilRight is applied and by substituting the current robot position with the CRG vector *AB* and the location of the kitchen is found as P_{kit}, the second precondition is instantiated to:

$$\exists P_2P_3 \in V.\ (\mathrm{kitchen}:P_{kit}) \wedge \langle AB,\ \mathrm{RightFront},\ P_{kit}\rangle \wedge \langle P_2P_3,\ \mathrm{RightBack},\ P_{kit}\rangle \wedge \langle AB,\ \mathrm{Front},\ P_2\rangle \wedge \langle AB,\ \mathrm{Front},\ P_3\rangle$$

  Then with the support of the SparQ toolkit, the instantiated preconditions are checked against the current state of the QSBM.

  If the current state matches the instantiated precondition, the current robot position is updated to P_2P_3 and a message object containing the success information is returned.

  If the current state provides e.g. the relations:

$$(\mathrm{kitchen}:P_{kit}) \wedge \langle AB,\ \mathrm{LeftFront},\ P_{kit}\rangle$$

  This means, the kitchen is located on the left side from the perspective of the robot and therefore, $\langle AB$, *RightFront*, $P_{kit}\rangle$ in the precondition cannot be satisfied. In this case, SimSpace creates a corresponding message which contains necessary information for indicating the failure of the interpretation and/or generating suggestion.
- According to the conceptual strategy and the returned message, either the interpretation continues if possible, or strategy dependent process is performed (e.g. in the RwB or QSRVT strategy), or appropriate responses or suggestions are made and presented back to the human user.

On the one hand, SimSpace can be used as a stand-alone evaluation platform for visualizing spatial environments, generating corresponding QSBM instances and testing the interpretation of natural language route instructions. On the other hand, it can also be used as a well encapsulated module and integrated into an interactive system to be used by a mobile robot to assist in the interaction with human operators.

4 An Empirical Study

In order to evaluate the qualitative knowledge based conceptual model and its implementation into a practical interactive system regarding the two different high-level conceptual strategies: reasoning with backtracking and QSR-value-tuples based searching, an empirical study was conducted.

4.1 Participants

Altogether 18 university students, with no background knowledge on cognitive science and therefore considered as novice users, participated in the study, in which 9 of them were interacting with the system using the strategy reasoning with backtracking, while the other 9 were testing the system with QSR-value-tuples based searching.

4.2 Stimuli and Apparatus

All stimuli were the same for each participant during the interaction process, e.g., visual stimuli were presented on a graphical user interface on a laptop displaying a map of an indoor environment with named landmarks, a robot avatar showing the current position of the robot, a possibly highlighted route along which the robot is going, and the clearly emphasized text of system response with respect to participants' instructions (see Fig. 7); audio stimuli of the system response were also generated as complementary feedback and played via the external speaker of the same laptop at a well-perceivable volume.

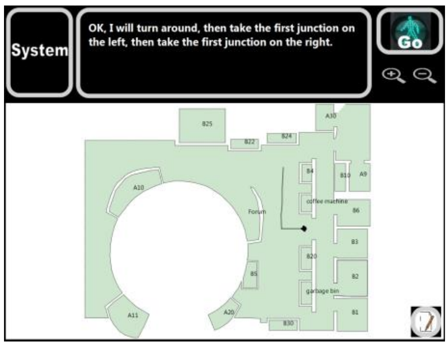

Figure 7: The graphical user interface with all visual stimuli

The same map of a floor plan of an indoor environment with the same virtual landmarks within this environment was used throughout the study.

The interactive system was a networked software system consisting of two laptops: one laptop, called the system laptop, hold the actual interactive system, which included the graphical user interface, interaction manager, speech synthesizer and the spatial knowledge processing component SimSpace that implemented the qualitative knowledge based conceptual model and the conceptual strategies; the other laptop, called the speech recognizer laptop, run a graphical interface, which was only operated by a human investigator and used to transfer the spoken natural language instructions to the system laptop via wireless network. The time for inputting natural language instructions is significantly shortened with a well-designed group of function-buttons on the speech recognizer laptop, so that only two seconds on average were needed for transferring utterances to the system laptop. As a result, the whole system was simulated as if each participant was giving instructions to the system using spoken natural language directly.

All participants were accompanied by the same investigator, who gave the introduction to the study and the system at the beginning, and input the natural language instructions of each participant into the speech recognizer laptop during the task performing through pressing the function buttons.

An internal automatic logging program of the system was used to collect interaction data such as dialogue turns, utterances, event time, and so on, while the standard audio recorder of windows recorded the whole dialogic interaction process.

Two questionnaires were conducted. The first one is called spatial ability questionnaire, which includes questions regarding abilities of describing routes to others, inquiring ways from others and using map in everyday life. This questionnaire aims to get the subjective assessment of each participant about his/her cognitive spatial abilities; the second questionnaire is called evaluation questionnaire, which concerns with the user satisfaction with the interactive system. Both questionnaires were based on 5-point Likert scale.

4.3 Procedure

For each test a participant had to undergo four steps:

1. Self-assessment: the participant was asked to fill the spatial ability questionnaire.
2. Introduction: the participant was given a brief introduction to the system and the following test runs, which included how to interact with the system and what to expect during the interaction.
3. Interaction: each participant was given five different tasks, each of which contains a starting position and a goal position. Only spoken language instructions were used to tell the robot to go from the starting position to the goal position. In order to collect more data and to produce more problem situations, for each task the participant had to describe two different routes or utter two different descriptions. Each task was ended, if either the goal position was reached, or the participant gave up trying.
4. Evaluation: after interacting with the system, the participant was asked to fill in the evaluation questionnaire.

5 Results and Discussion

According to the general view of the well accepted evaluation framework Paradise (Walker, et al 1997), the performance of an interactive system can be measured via the effectiveness, the efficiency and the user satisfaction. Thus, we have performed the analysis of the data from the interactive system on the two conceptual strategies with respect to these three aspects.

Even with the relatively small group of the participants (9 persons in each group), the authors believed that the comparison of the presented empirical results between the two groups can be considered representative, since the grouping was performed in a random manner, and furthermore, the results of the self-assessment of the spatial ability are similar between the two groups with the values of 53.2 and 51.9 on average.

5.1 Regarding the Effectiveness

The study was conducted with a Wizard of Oz setting without an automatic speech recognizer, therefore, the effectiveness of the interactive system could only depend on whether the subtasks were successfully performed, namely, whether the navigation goals were reached or not. 10 Goals were supposed to be reached by each participant. With 9 participants for one strategy, the number of reached goals are counted and summarized in table 1.

	RwB	QSRVT
Reached Goals (percentage)	85 (94.4%)	90 (100%)

Table 1: Effectiveness with RwB and QSRVT

For both strategies, the effectiveness of performing navigation tasks with the interactive system is very good. The participants using the RwB strategy reached 85 goals out of 90, while the ones using the QSRVT strategy reached all the goals.

5.2 Regarding the Efficiency

In order to find out how efficiently each participant was assisted with the interactive system using the two different strategies, the automatically logged data were analysed according to the average elapsed time and interaction turns for each task. The results are summarized in table 2.

	RwB		QSRVT		P Value
	Mean	Std.	Mean	Std.	
Average Elapsed Time (s)	87.37	33.13	48.12	9.14	0.007
Average Interaction Turns	7.14	2.91	4.07	0.68	0.013

Table 2: Data concerning efficiency for each participant and each task

From a general perspective for task performing, a very good efficiency is shown with 87.37 seconds and 7.14

interaction turns on average for each task with the RwB strategy, since this also includes some very long system responses, some of which even needed over 20 seconds to be played. The standard deviation of 33.13 for elapsed time is however a bit high, this is mainly due to one certain participant who confused the left/right relations too often and used over 150 seconds on average to finish one task, which, however, is not common for the other participants.

Moreover, the performance efficiency with the QSRVT strategy is much better: each participant only used 48.12 seconds and 4.07 turns on average to finish one task. The p-values of 0.007 and 0.013 also indicate that the participants with the QSRVT strategy could perform tasks significantly more efficiently than those with the RwB strategy.

5.3 Regarding the User Satisfaction

Regarding the user satisfaction about the interactive system, the subjective data of the evaluation questionnaire filled by each participant after task performing were analysed and summarized in table 3.

	RwB		QSRVT	
	Mean	**Std.**	**Mean**	**Std.**
System Response	3.36	0.79	4.0	0.52
General Support	3.94	0.80	4.25	0.41
Future use	3.72	0.49	3.94	0.62
Total	3.68	0.63	4.06	0.43
Total / Skill	0.07	0.02	0.08	0.01

Table 3: Data concerning user satisfaction

The overall user satisfaction of the interactive system with the RwB strategy for each participant is considered at a satisfactory level with the total average value of 3.68 and standard deviation 0.63. Specifically, they found the system response sufficiently understandable with the value 3.36, they felt supported by the system with the value of 3.94 and they would recommend the system with the value of 3.72. The standard deviations of 0.79 for system response and 0.80 for general support are a bit higher, this is because of the special situations where the RwB strategy encounters with missing instructions and therefore the system could not provide very useful information about the communication problems.

Meanwhile, the user satisfaction of the system with the QSRVT strategy was improved from every perspective, 4.0 for the system response, 4.25 for the general support, 3.94 for the future use and all together 4.06.

With the data from the self-assessment questionnaire, a skill value is calculated and shows how confident each participant considers him- or herself to be with spatially-related tasks. The ratios of the total satisfaction degree and the skill value of 0.07 and 0.08 also roughly indicate that, the QSRVT strategy better assists the participants also in a more or less subjective manner than the RwB strategy does.

6 Conclusion and Future Work

In this paper we reported our work on using conceptual model to support human robot collaborative navigation, focusing on the following three important aspects:

- the design and development of a qualitative spatial knowledge based multi-level conceptual model for human robot interaction,
- the implementation of the conceptual model and the model-based high-level conceptual strategies within a general computational framework, and
- the evaluation of an interactive system built on the conceptual model, framework and strategies.

The positive empirical results validated our effort on developing and implementing the proposed conceptual model and framework. It was also shown that, the model based high-level conceptual strategies, especially the strategy of QSR-value tuple based searching can assist the mobile robot to clarify more spatially-related communication problems and better support the human-robot collaborative navigation.

The presented work served as a fundamental step towards building robust, effective, efficient, user-friendly models, frameworks and interactive systems in spatially-related applications. The integration of the conceptual model, framework and strategies into a real mobile robot for spatial navigation with untrained human operators is being conducted. For the strategy of QSR-value tuple based searching, learning-based QSR-value updating is being investigated. We are also considering adding other qualitative spatial calculi into the QSR model level to support further application, such as object localization within complex buildings. Human-robot collaborative exploration in unknown or partially-known spatial environments is also a work package to be pursued.

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