Navigation with the Dipole Calculus

Germán CARRILLO and Christoph MÜLLIGANN
Institute for Geoinformatics, University of Münster

Abstract. We present an algorithm that enables robots to navigate a street network with a minimum of local and global knowledge using the Dipole calculus for qualitative spatial representation of line segments. A constraint-based approach is employed where decisions are made based on relational constraints imposed on possible route alternatives. We also provide a simulation to evaluate the usefulness of the navigation algorithm.

Keywords. qualitative spatial reasoning, dipole calculus, navigation

1. Introduction

Navigation represents one of the core tasks performed by humans in space. Since they widely succeed in performing spatial reasoning with qualitative relations instead of numeric operations, qualitative spatial reasoning (QSR) has not only become important to spatial cognition research but also to robot navigation in particular and artificial intelligence in general. Building a numeric model of the environment where navigation is performed may be too complex because of the sensory and computational capabilities of the robot, data incompleteness or simply mask higher-order features that can be represented and used for reasoning comparably easy in qualitative terms [5]. A street network can be considered such a case. Here the imposed movement constraints require decision making only at junctions and even there the alternatives are limited to the connected streets.

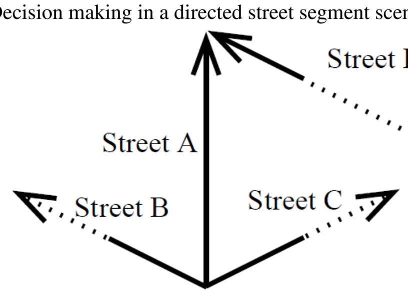
In this work we present an algorithm that enables robots to navigate a street network with a minimum of local and global knowledge using the Dipole calculus [9] for qualitative spatial representation of line segments. We follow a constraint-based approach in the sense of [12] where decisions are made based on relational constraints imposed on possible route alternatives. A simulation is provided to evaluate the usefulness of the navigation algorithm prior to a field test. In section 2 we give an overview of qualitative reasoning research for navigation relevant in the broader scope of our work. Next, we define the problem that is being adressed in section 3. After presenting the algorithm in section 4, a description of the simulated results is given in section 5. Finally, we conclude our findings and point to further work in section 6.

2. Related Work

Even though navigation is a classic QSR application, there is a wide range of different scenarios impacting the use of calculi. For instance, approaches [2,4,10] relying on landmark knowledge mostly employ the double-cross-calculus [3]. Others do not use calculi for navigation itself but for both ways of human-computer interaction such as movement instructions [11] or route descriptions [15]. Approaches also differ by the modelled space: while in [4,10,11,13] the extent of accessible spatial entities is two-dimensional, the approach of Escrig and Toledo [2] as well as Westphal et al. [15] is like ours based on movement on line segments in a street network. Lücke et al. [7] as well as Dylla and Wallgrün [1] deal with navigational issues of the OPRA calculus [8] and in that course the latters provide a mapping from OPRA to the extended Dipole calculus (DRA72). The OPRA, double-cross and cardinal directions calculus [6] have also been used for map learning or robot exploration respectively [10,13], a task similar to navigation but aiming at assessing a consistent and unambiguous interpretation of an environment instead of reaching a specific location.

A qualitative calculus is built upon operations performed on a set of relations between objects [14]. These relations are a way to express qualitative knowledge and when dealing with space they mainly represent topology, orientation or distance [12]. The Dipole Relational Algebra (DRA)-24 proposed by Moratz et al. [9] is based on 24 relations between pairs of oriented line segments. They are expressed in terms of their start and end points. The dipole relation schema is $A\ R\ \mathtt{s}_B$, $A\ R\ \mathtt{e}_B$, $B\ R\ \mathtt{s}_A$, $B\ R\ \mathtt{e}_A$ where A and B are the two dipoles, $\mathtt{s}$ and $\mathtt{e}$ are the start and end points of A or B and R is one of $\{l, r, s, e\}$ (*left, right, start, end*). For instance, $A\ l\ \mathtt{s}_B$ denotes that the start point of B lies to the left of A and $A\ s\ \mathtt{s}_B$ that the start point of B is connected to the start point of A. The short form of the relation schema then only contains R in the above mentioned order. In figure 1, for example, the dipole relation between street A and street B is $A\{slsr\}B$.

Figure 1. Decision making in a directed street segment scenario. Source: [9]



The configuration of dipoles (scenario) in a network can be described by a set of relations. However, there can be sets of relations describing inconsistent scenarios. Given a scenario one could add hypothetical relations (constraints) to check the consistency of unknown scenarios and thus gain knowledge. This approach is given by Moratz et al. [9] in a sample application of the calculus and it represents the basis of the algorithm we propose. Figure 1 shows a setting where initial knowledge given by $A\{slsr\}B$, $A\{srsl\}C$, $A\{rele\}D$ is checked for consistency against two constructed relations $B\{ells, errs\}D$ and $C\{ells, errs\}D$ in order to navigate a car from the T-crossing to street D. Since both constructed relations comprise the situations where B and D, as well as C and D meet respectively, we refer to them as *MEET* relations. If consistency holds for the first *MEET* relation the car is supposed to take street B, C otherwise. Note that in Moratz' scenario there are only one-way streets (so street A cannot be taken to reach a location on street D) while our algorithm is designed for the more general case of a bidirectional network.

3. Problem Statement

Robots or other moving objects with spatial reasoning capabilities usually have limited information to their disposal. In the case of navigation on line segments, for example, they might not know the whole street network. Even if that was the case keeping track of the own position within the network is an issue. The navigation algorithm presented in this work is a solution to the scenario where the robot has sensory devices allowing it to assess the spatial relations of changing local scenes such as crossings as well as the relation to a single but remote target street segment. Since the robot is required to sense this kind of global knowledge at any point there is no need for any long-term memory except for the case of turn backs in dead-ends.

The aim of our algorithm is to actually simulate the movement of a robot instead of global path optimization. Decision making based on the Dipole calculus, being one of the most simple representations of spatial knowledge, potentially yields many alternative routes from which the robot would have to pick one randomly. However, we claim that even a minimum of qualitative information can greatly increase the navigation performance compared to, e.g., blindly exploring a street network. Due to the simplicity of the Dipole calculus our approach is especially relevant for robots with limited sensory capabilities.

4. Algorithm

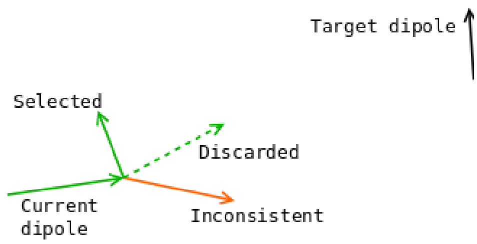
We propose a navigation algorithm based on iterative decision-making of the kind explained in [9], see section 2. The following pseudo code is a set-based version of our algorithm where the movement of a robot is represented by changes of `current_dipole`:

```
INPUT start_dipole, target_dipole
SET meet_relation to "(ells errs lere rele)"
PUSH start_dipole to selected_dipoles
WHILE candidate_dipoles do not contain target_dipole
    IF selected_dipoles is not empty THEN
        POP current_dipole from selected_dipoles
    ELSE
        POP current_dipole from backup_dipoles
    ENDIF
    GET current_target_relation by calling QUALIFY of
        current_dipole and target_dipole
    GET candidate_dipoles leading away from the end point of
        current_dipole by calling OUTGOING_DIPOLES of current_dipole
    IF candidate_dipoles do not contain target_dipole THEN
        IF size of candidate_dipoles = 1 THEN
            POP candidate_dipole from candidate_dipoles
            PUSH candidate_dipole to selected_dipoles
```

```
          ELSE
              IF size of candidate_dipoles > 1 THEN
                  FOR each candidate_dipole in candidate_dipoles
                      GET candidate_current_relation by calling QUALIFY
                          of candidate_dipole and
                          current_dipole
                      GET isConsistent by calling SCENARIO_CONSISTENCY
                          of current_target_relation,
                          candidate_current_relation and meet_relation
                          between candidate_dipole and target_dipole
                      IF isConsistent THEN
                          PUSH candidate_dipole to selected_dipoles
                      ELSE
                          PUSH candidate_dipole to backup_dipoles
                      ENDIF
                  ENDFOR
              ENDIF
          ENDIF
      ENDIF
  ENDWHILE
```

Beyond the structural keywords, PUSH and POP denote stack operators and GET external function calls. Three external functions are used, the SparQ[1] modules QUALIFY and SCENARIO_CONSISTENCY for converting quantitative geometric scenarios into qualitative ones (based on relations) and checking consistency of dipole configurations as well as OUTGOING_DIPOLES, which in the case of robot navigation is the local view provided by sensory devices or, in the simulation case, access to a subgraph of the street network. Beside the QSR-enabled distinction between "good" and "bad" route segments we also consider dead-end and multi-segment streets. The former requires the robot to store route memory (selected_dipoles and backup_dipoles) for backtracking in order to ensure that it always reaches the target segment. If this is not postulated the robot may theoretically lack any long-term memory. In figure 2 there are two consistent dipoles to choose from. If it turns out that the "selected" dipole is a dead end, the "discarded" dipole is used instead.

Figure 2. An iteration of the algorithm where local and global knowledge is used for selecting a dipole based on consistency checking.

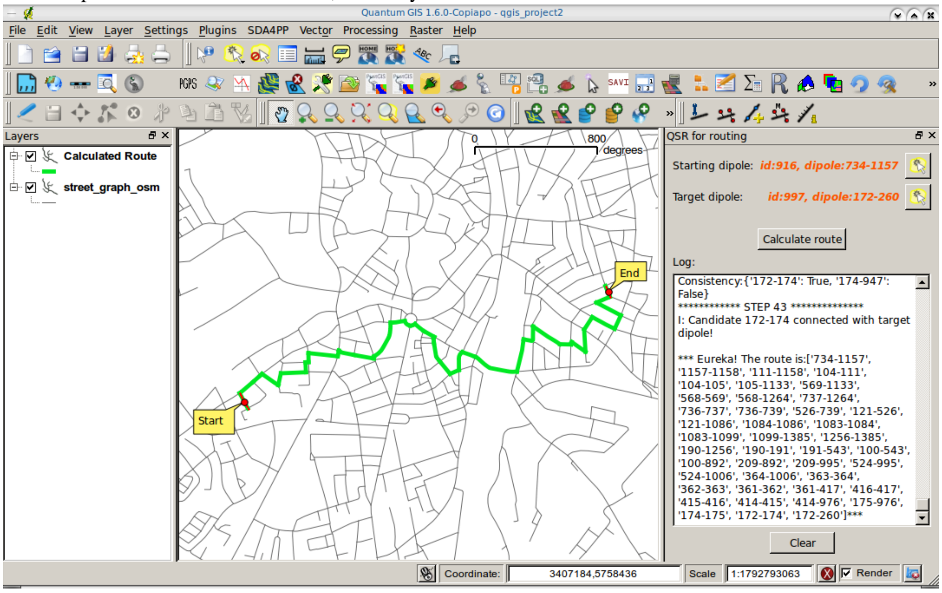


[1] http://www.sfbtr8.uni-bremen.de/project/r3/sparq/

5. Results

The implementation consists of a Quantum GIS plug-in written in Python, which can be downloaded from [2]. After the user selected start and target segment, the calculated route is converted into a memory Shapefile and shown in QGIS as a new layer on the map. The plug-in also prints logging messages to understand the whole process in terms of reasoning steps.

Figure 3. The Quantum GIS plug-in and exemplary simulation results based on an extract of the OpenStreetMap [3] street network of Münster, Germany.



It can be noticed from figure 3 that the result is neither the shortest nor the simplest route (with regard to the number of turns) but far from being a random search. It may happen that small detours are made when picking one out of several "consistent" streets randomly. However, despite of the coarse qualtitative knowledge representation provided by the Dipole calculus the navigation algorithm heads towards the target quite reliably.

6. Conclusion

In this work we have used qualitative spatial reasoning for simulating the movement of a robot in a network composed of line segments. The Dipole calculus was employed for reasoning that consists of no more than qualifying relations between street segments and scenario consistency checks. The simulation was implemented as a freely available Quantum GIS plug-in and yields encouraging results in the sense that even a minimum

[2]http://downloads.tuxfamily.org/tuxgis/geoblogs/qsr_routing/zeitgeist2012/QualitativeRoute.zip

of qualitative spatial knowledge can increase the navigation performance of a robot compared to a random target search. Further work goes into the direction of finer-grained decision making, either by including more spatial knowledge or more sophisticated scenario descriptions to be checked for consistency.

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