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REPRESENTATION OF MOVING OBJECTS ALONG A ROAD NETWORK

Nico Van de Weghe[1], Anthony G. Cohn[2], Peter Bogaert[1] and Philippe De Maeyer[1]
[1]Ghent University - Department of Geography, B-9000 Gent (Belgium), {Nico.VandeWeghe, Peter.Bogaert, Philippe.DeMaeyer}@UGent.be, Tel: +32 (0)9 264 46 96, Fax: +32 (0)9 264 49 85
[2]University of Leeds, School of Computing, Leeds LS2 9JT, United Kingdom, agc@comp.leeds.ac.uk

Abstract

Research has previously been conducted in the area of generating, indexing, modelling and querying network-based moving objects. However, little work has been done in building a calculus of relations between disconnected network-based mobile objects. In this paper an approach to qualitatively representing and reasoning about trajectories of pairs of objects moving along a road network is presented. We call this approach the "Qualitative Trajectory Calculus along a road Network" (QTCN). We start from the assumption that two objects are moving continuously towards each other or away from each other, and consider how to describe their joint trajectories. Since the distance between two objects is measured along the shortest path, specific attention will be given to changes in shortest path, and more specifically changes in direction of the velocity vector of an object with reference to the shortest path between two objects. A conceptual neighbourhood diagram is presented, that forms the basis for a representation of a conceptual animation.

INTRODUCTION

The most developed area of qualitative spatial representation concerns topological relationships, as exemplified by RCC (the Region Connection Calculus) (Randell et al., 1992) in which connection between spatial regions can be taken as a primitive notion to define many other spatial relations between them, including the eight base relations depicted in Figure 1. Assuming continuous motion, there are constraints, which can be imposed upon the way these base relations can change over time for any pair of spatial regions (Figure 1). The 4-intersection model gives a similar calculus (Egenhofer and Franzosa, 1991).

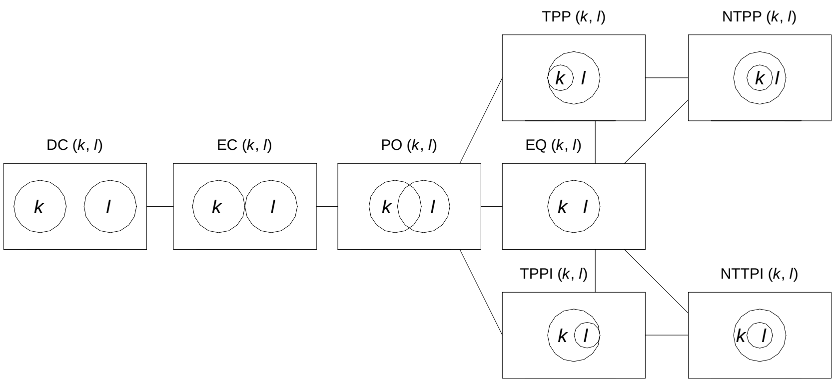

Figure 1: The continuous transitions between the eight base relations of RCC.

There are two types of moving objects (Moreira et al., 1999): those having a free trajectory such as a bird flying through the sky and those with a constrained trajectory in which the movement of an object in space is strongly restricted due to physical constraints, e.g. a vehicle driving through a city. In Van de Weghe et al., (2004) the Qualitative Trajectory Calculus (QTC) is presented for representing and reasoning about the trajectories of pairs of moving objects (abstracted to point-locations), which provides a technique for many free trajectory applications. In this calculus, the movement of two objects (*k* and *l*) is qualitatively represented using three functions (resulting in 27 trajectories):

1. movement of *k* towards *l* (– : to *l*, + : away from *l*, 0 : stable).
2. movement of *l* towards *k* (– : to *k*, + : away from *k*, 0 : stable).
3. speed of *k* (v_k) wrt *l* (– : $v_k < v_l$, + : $v_k > v_l$, 0 : $v_k = v_l$).

Research has been conducted in generating (Brinkhoff, 2002; Pfoser and Theorodidis, 2003), indexing (Frentzos, 2003; Pfoser, 2002), modelling (Vazirgiannis and Wolfson, 2001) and querying (Shahabi et al., 2001) network-based moving objects. However, little work has been done in building a calculus of relations between disconnected network-based mobile objects, which is the focus of this paper. In this paper, QTC is extended for movements of objects along a road network, resulting in the specialised calculus, which we call the *Qualitative Trajectory Calculus along a road Network* (*QTCN*). For simplicity we will ignore the speed constraint (third character) in this paper. Therefore the 27 QTC trajectories (3^3) are reduced to 9 (3^2) trajectories (see Figure 2).

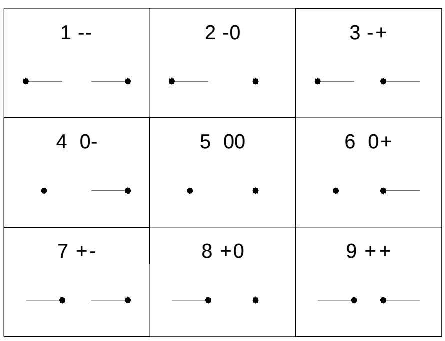

Figure 2: Visualization of the 9 trajectory descriptions of QTCN.

SOME CENTRAL TERMS CONCERNING GRAPH THEORY

To model a road network, one can use the mathematical model found in graph theory (Miller and Shaw, 2001). A *graph G*(*V*, *E*) is defined by a set of *edges E* and a set of *vertices* or *nodes V*, such that every edge is *associated with* or links exactly two vertices (possibly identical in case of an edge linking a vertex to itself - a *reflexive edge*). In the model of a *road network*, an *edge* represents a road between two *nodes*, which can have different *degrees*; degree 1: dangling node, degree 2: pseudo node, degree≥3: junction (see Figure 3).

A *subgraph* G'(V', E') of G(V, E) is simply defined by a subset E' of the edges and a subset V' of the vertices. A *path* is a subgraph G'(V', E') of the entire graph such that: no node of G' has degree more than two, and at most two nodes have degree one, and every vertex of G' is incident in at least one edge in E' and there is no superset of G' in G having these properties. The *shortest path* between two objects is a path between both objects (inserted as nodes in the network) whose total cost is the least among all such paths. The cost (e.g. distance, travel time) is usually the sum of the arc costs. The shortest path is a key term in QTCN since it will be the reference frame to measure the distance between two objects *k* and *l*.

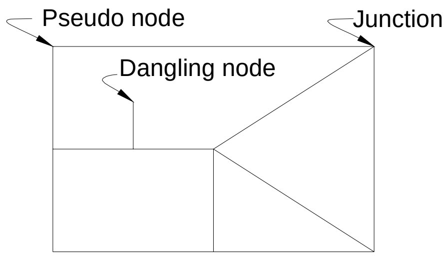

Figure 3: Degree of a node.

QUALITATIVE TRAJECTORY CALCULUS ALONG A ROAD NETWORK

Empirical Approach of QTCN Based on an Illustrative Example

In this section, we will illustrate the use of QTCN. Consider the network presented in Figure 4, with two objects (*k* and *l*) moving along this network from time stamp t_0 to time stamp t_{10}. In Figure 4, the space-time paths of both objects are represented in a space-time cube. Since this representation depicts three dimensions (2 space and 1 time dimension) in 2D, visual analysis is perhaps not particularly easy. Therefore, Figure 4 is re-represented as Figure 5 which will be used as a basis to describe the spatio-temporal evolution of the interaction between both objects.

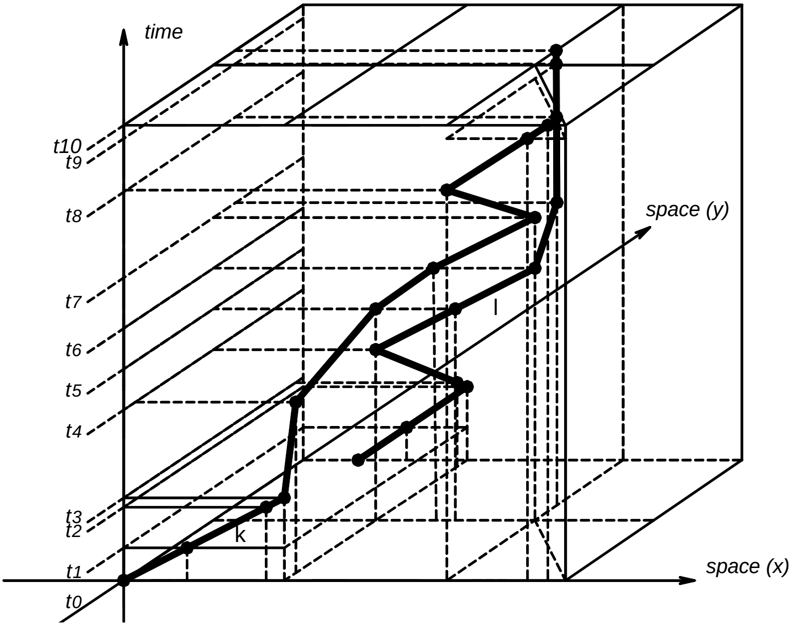

Figure 4: Movement of two objects along a network: space-time cube.

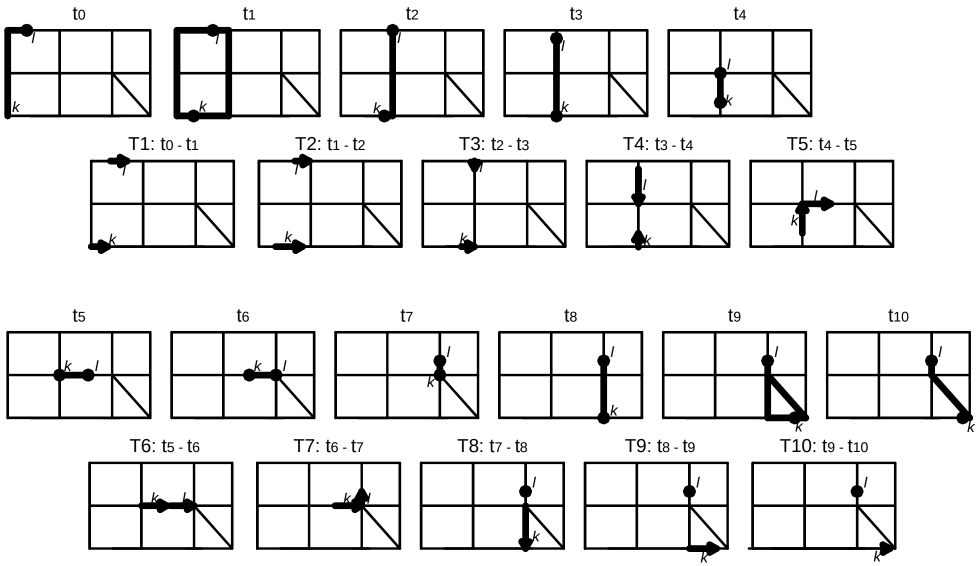

Figure 5: Movement of two objects along a network: snapshots and transitions.

For each time stamp (from t_0 to t_{10}) the location of the object is given, along with the shortest path between both objects at that moment in time (depicted with a thick line in Figure 5). At t_0 for example, the shortest path between *k* and *l* starts at *k* (located at the bottom left node), then heads north (assuming up represents north), until it heads east to arrive at object *l*. In addition, every transition between time stamps (from *T1*: t_0 - t_1 to *T10*: t_9 - t_{10}) is represented. Two arrows respectively starting in object *k* and object *l*, represent the movement of these objects from the beginning to the end of these transitions. During *T1*: t_0 - t_1 (starting just after t_0 and ending just before t_1), *k* and *l* move to the east. In other words: the velocity vector of both objects has a direction to the east (Note that we do not represent the orientation of a trajectory (e.g. east) in this paper, although that would be a possible extension to the calculus).

QTCN descriptions can hold either at (instantaneous) time stamps, or in the (open) intervals between them. Although instants have no duration, these transitions (Cf. Forbus' *equality change law* in Weld and de Kleer, 1990). become very important in analyzing the qualitative evolution of the space-time paths and in the construction of the conceptual neighbourhood diagram (see below). In each of the transitions mentioned above, the descriptions for the open intervals can be read off from the diagrams in Figure 5 directly by considering the direction (away/along the shortest path) of the velocity vectors: *T1* (t_0, t_1) (*k*, *l*) + + ; *T2* (t_1, t_2) (*k*, *l*) – – ; *T3* (t_2, t_3) (*k*, *l*) – – ; *T4* (t_3, t_4) (*k*, *l*) – – ; *T5* (t_4, t_5) (*k*, *l*) – + ; *T6* (t_5, t_6) (*k*, *l*) – + ; *T7* (t_6, t_7) (*k*, *l*) – + ; *T8* (t_7, t_8) (*k*, *l*) + 0 ; *T9* (t_8, t_9) (*k*, *l*) + 0 ; *T10* (t_9, t_{10}) (*k*, *l*) – 0.

We give a little more detail now. Between t_0 and t_1, both objects move to the east, but what is more important from the point of view of the presented calculus is the relative direction of both objects compared to the shortest path. During *T1*, both objects *k* and *l* move away from the shortest path; in other words: the velocity vector of *k* and the shortest path between *k* and *l* only overlap in one single point, namely the location of object *k* at t_0, and the same is true for object *l*. This so-called *shortest path constraint* is reflected in the first and the second character of the QTCN-label, both being +. Thus *T1* will be labelled as *T1* (*k*, *l*) + +. Following the same reasoning process one can label *T2* as *T2* (*k*, *l*) – –. Comparing *T1* and *T2* we note that both the first and the second character transition directly from + to – without taking on an intermediate value of 0; in the qualitative quantity spaces developed by the Qualitative Reasoning community (Weld and de Kleer, 1990), such a transition would be discontinuous. However, both objects' motion is clearly continuous; the solution is to note that there has been a change in shortest path at t_1 – this can be clearly seen in Figure 5, as there are two shortest paths at t_1. This has resulted in a change in the direction of the velocity vectors of the objects with reference to the shortest path. In this particular case, this change occurred around object *k* (resulting in a change of the first character) as well as around object *l* (resulting in a change of the second character). At t_1, *k* and *l* are neither moving toward nor away from each other, but transitioning between these two states; i.e. the movement is neither along the shortest path, nor away from it. Whenever the motion of an object flips along or away from the shortest path, this kind of instantaneous transition will occur; for example at t_9, there are again two shortest paths depicted in Figure 5 – see below.

The descriptions for the instantaneous time points separating the intervals are governed by the descriptions of the intervals around them. In some cases (t_2, t_3, t_5, t_6, and t_8), the descriptions of the surrounding intervals are identical, so the description at the instant simply replicates these descriptions. In other cases, similar considerations to our discussion above about continuous motion, force particular characters to take on a value of 0. This will occur if there is a fluctuation in shortest path constraint from just before to just after the specific time stamp. Around t_4 for example, both velocity vectors move towards the shortest path, which resulted in *T4* (t_3, t_4) (*k*, *l*) – –. Just after t_4 there is a change in the relative direction of the velocity vector of object *l* with reference to the shortest path, resulting in *T5* (t_4, t_5) (*k*, *l*) – +. Therefore t_4 will be labelled t_4 (*k*, *l*) – 0. An analogous remark can be made for t_7, resulting in t_7 (*k*, *l*) 0 +. Simultaneously another interesting thing happens at t_7: just before, *l* is moving, and just afterwards, *l* is stationary (Note that whereas in free space (Van de Weghe et al., 2004), a value 0 of motion might mean that the object is stationary or that it is circling around the other, given the constraints of the road network, only the former interpretation is possible). Now, what is the appropriate description for the second character at t_7? Clearly *l* is slowing down (We do not currently represent acceleration, though this would be a natural extension to the speed descriptor present in Van de Weghe et al., 2004), and Forbus' equality change law (Weld and de Kleer 1990) states that an interval-like qualitative value (+ or – in QTCN) will reach a landmark value (0 in QTCN) at a time instant; thus the second character of the description at t_7 must be 0 rather than +, which will result in the label for t_7 (*k*, *l*) 0 0.

As already mentioned before, there is a change in shortest path at t_9. However there is a difference compared to the shortest path change at t_1. Since *l* is stationary, there will only be a change in value of the first character from *T9*, over t_9 to *T10*. Note that being stationary is superior to the shortest path constraint. In this example, a low speed of *l* would not change the QTCN-label but a larger speed would change the shortest path between *k* and *l*. This would change the direction of the velocity vector with reference to this shortest path, resulting in a change of the first character of the label.

Note that we have not given a description for what holds instantaneously at t_0. Without further information, the situation there is ambiguous; for example all objects might be at rest, (0 0), or just *k*, (0 +), or there may have been a previous interval just before t_0 when the objects were both moving in a similar fashion, (+ +), in which case + + would also hold at t_0. An analogous remark can be made for t_{10}.

Combining all of the above analysis will result in a list of all the relative trajectories, which has been called a *conceptual animation* in (Van de Weghe et al., 2004): $T1$ (t_0, t_1) (k, l) + + ; t_1 (k, l) 0 0 ; $T2$ (t_1, t_2) (k, l) – – ; t_2 (k, l) – – ; $T3$ (t_2, t_3) (k, l) – – ; t_3 (k, l) – – ; $T4$ (t_3, t_4) (k, l) – – ; t_4 (k, l) – 0 ; $T5$ (t_4, t_5) (k, l) – + ; t_5 (k, l) – + ; $T6$ (t_5, t_6) (k, l) – + ; t_6 (k, l) – + ; $T7$ (t_6, t_7) (k, l) – + ; t_7 (k, l) 0 0 ; $T8$ (t_7, t_8) (k, l) + 0 ; t_8 (k, l) + 0 ; $T9$ (t_8, t_9) (k, l) + 0 ; t_9 (k, l) 0 0 ; $T10$ (t_9, t_{10}) (k, l) – 0.

Note that at t_2, t_3, t_5, t_6, and t_8, the descriptor at the time instant, and just before and after is the same. Thus these time instants do not separate different qualitative states as the other (non terminal) time instants do. If we were to follow the tradition of qualitative reasoning, then a minimal description would not include these instants, and the surrounding intervals of each of these instants would be merged: $T1$(t_0, t_1)(k, l) + +; t_1(k, l) 0 0; $T2'$(t_1, t_4)(k, l) – –; t_4 (k, l) – 0 ; $T5'$ (t_4, t_7) (k, l) – + ; t_7 (k, l) 0 0 ; $T8'$ (t_7, t_9) (k, l) + 0 ; t_9 (k, l) 0 0 ; $T10$ (t_9, t_{10}) (k, l) – 0.

Also worth pointing out is that we have been careful to explicitly include a time point whenever a shortest path "flip" occurs. If we had not done this, then it would have been difficult to assign a qualitative description to the interval which contained this "flip". The process of *limit analysis* described by Forbus in Weld and de Kleer (1990) shows how such instants can be discovered automatically.

Conceptual Neighbourhood Diagram

In 1992, Freksa introduced the important idea of *conceptual neighbourhood* (which is strongly related to the *continuity table* to be found in Randell and Cohn, 1989). According to Freksa: 'Two relations between pairs of events are *conceptual neighbours*, if they can be directly transformed into one another by continuously deforming (i.e. shortening, lengthening and moving) the events in a topological sense'. In QTC, two trajectory pairs are conceptual neighbours if they can directly follow each other during a continuous movement (Van de Weghe et al., 2004). In Figure 6 the conceptual neighbourhood diagram on QTC is transposed into the conceptual neighbourhood diagram on QTCN. Note the difference between single and dual change of shortest path constraint.

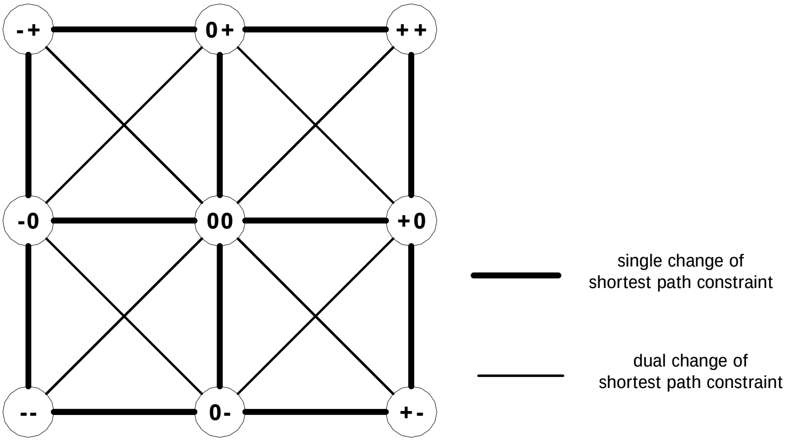

Figure 6: CND of the QTCN.

The conceptual animation can be drawn as a diagram (see Figure 7). Note that the nodes correspond to those in Figure 6 (and thus inherit the QTCN descriptions on each node).

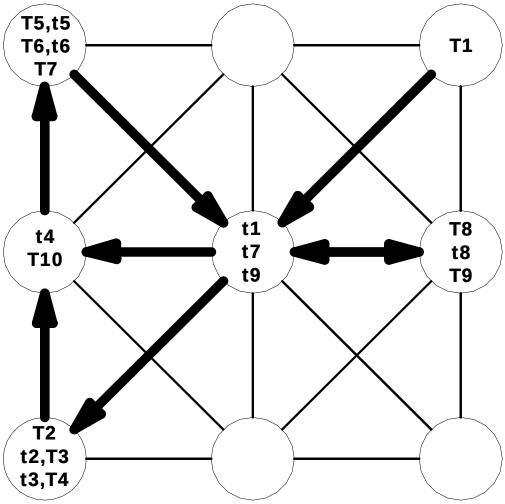

Figure 7: Conceptual animation represented on the CND of the QTCN.

FUTURE WORK

In future work we plan to extend QTCN with a third and a fourth character standing for respectively the relative speed and the relative acceleration of two objects. Another possible extension is from two moving objects to *n* moving objects.

Since this will increase the complexity drastically, a more formal approach to QTCN will be worked out. We plan to state and prove when the relative trajectory between two objects *k* and *l* will change. We will also focus on how the relative trajectory between two objects can be calculated using the tables utilized in shortest path calculations. Defining the composition table is also important (the composition table specifies the relationship between *k* and *m,* given the relationship between *k* and *l,* and the relationship between *l* and *m).*

We believe this work can form the base of an in depth study of objects moving along networks in real life assuming benchmarking, indexing, modeling and querying of moving objects.

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