Efficient Storage of Interactions between Multiple Moving Point Objects

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Abstract. The quintessence of the Qualitative Trajectory Calculus – Double-Cross (QTC_C) is to describe the interaction between two moving objects adequately. Its naturalness has been studied before, both theoretically and by means of illustrative examples. Using QTC_C, this paper extends the fundamental approach to interactions of configurations of multiple moving objects. In order to be able to optimally store and analyse trajectories of moving objects within QTC_C, a transformation from traditional quantitative information to QTC_C information is needed. This process is explained and illustrated by means of an example. It is shown that once this transformation process is done, the storage and analysis of real world moving objects from the point of view of QTC_C, enables querying of moving objects.

1. Introduction

The use of spatio-temporal relations to define the motion of objects is an important issue in many domains. Besides traditional research areas such as geography, geology, archaeology, and different socio-economic disciplines (e.g. criminology and transportation), research domains in computer science such as, spatial databases, video retrieval and robotics extensively use this type of spatio-temporal data. In most spatial software packages, the absolute positions of spatial entities are represented by sets of coordinates in a Euclidean space, and information is extracted by means of arithmetic computations. In particular, numerical representations may be well suited where precise spatial information of a definite situation is available, and if the output required from the system is itself primarily numerical [1]. However, quantitative information tends to be less available and more expensive than its qualitative counterpart [2]. Additionally, quantitative information is often too precise for the given spatial context. For example, if we want to show a person the way to get to the train station, we do not need to be more precise than, just indicating the streets he has to follow. It has also been recognised that a qualitative approach is more appropriate for the representation of spatio-temporal human cognition than a quantitative one [3]; certainly, since the major goal of many reasoning processes is being able to take a decision be it rather qualitative than quantitative [2].

In the last two decades, qualitative formalisms suited to express qualitative temporal or spatial relations between entities have gained wide acceptance as a useful way of abstracting from the real world. Temporal (e.g. [4, 5]) and spatial (e.g. [6, 7]) calculi have been proposed. Despite extensive research during the past decade, both from the area of spatio-temporal reasoning (e.g. [8, 9]) and databases (e.g. [10, 11, 12]), there are still many unresolved issues in the representation of and reasoning about space-time. One important remaining question is how to adequately describe motion, and more specifically, the interaction between moving objects, within a qualitative calculus. Apart from some limiting cases such as the reconstruction of a car accident and a predator catching a prey where moving objects *meet*, mobile objects such as traffic flows, and movements of people and animals are represented by use of the relation *disconnected from* in the widely used RCC- Calculus [6] and 9-Intersection Model [7]. It is clear that this approach ignores some important aspects of reasoning about continuously moving physical objects. For example, given two trains on a railroad or two planes in the air, it is important to know their movement with respect to each other in order to avoid potential collision. In other words, a challenging research question is: 'how to represent and handle changes in movement between moving objects, if there is no change in their topological relationship?' Answering this question implies developing a new formalism. This shortcoming is adressed in [13], where the Qualitative Trajectory Calculus (QTC) is advanced. QTC is a theory for representing and reasoning about movements of objects in a qualitative framework, differentiating groups of disconnected objects. Depending on the level of detail and the number of spatial dimensions, different types of QTC have been defined, all belonging to two variants: QTC - Basic (QTC_B) or QTC - Double Cross (QTC_C). Several issues of QTC have been studied before: [14, 15, 16]. In the current paper, we want to go into further detail on two specific topics concerning QTC_C. In Section 2, we extend the fundamentals of QTC_C where only two objects are moving to cases where there is an interaction between more than two objects. In Section 3, we discuss the need to transform quantitative intervals to QTC_C intervals. This issue is becoming more and more important due to the increased development of Moving Object Databases. We work out the methodology in detail by means of an illustrative example.

2 The Qualitative Trajectory Calculus – Double-Cross (QTC_C)

2.1 Fundamentals of QTC_C

In this section, QTC_C is briefly presented. For further reading, we refer to [13]. Continuous time for QTC_C is assumed. QTC_C is partly based on the Double-Cross Calculus introduced by Freksa and Zimmermann [2, 17]. QTC_C examines the movement of 2 point objects k and l with respect to each other. The movements of both point objects k and l are represented by a vector (Fig. 1(a)), degenerated to a point if an object is not moving (Fig. 1(b)). Through the origins of these vectors, the reference line (RL) is defined. Also through these origins and perpendicular to RL, $RL\perp 1$ and $RL\perp 2$ are defined. RL, $RL\perp 1$, and $RL\perp 2$ form the double-cross, being the reference frame for QTC_C. Two dichotomies form the basis of the reference frame: towards/away-from and left/right. The first results in the first character (char1) and char2 of the QTC_C label. The second dichotomy also results in 2 characters: char3 and char4. By reducing the continuum to the qualitative values –, 0 and +, the underlying continuous system can be described in a qualitative way. Hence, a 2D movement is presented in QTC_C using the following four conditions (C1, C2, C3, and C4).

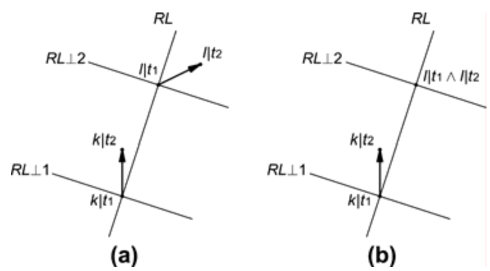

Fig. 1. Reference frame for QTC_C: (a) two objects moving; (b) one object moving.

We introduce the following notations for QTC_C:

objects k and l,
RL_{kl} denotes the directed reference line from k to l,
$x|t$ denotes the position of an object x at time t,
$d(u,v)$ denotes the distance between two positions u and v,
$v_x|t$ denotes the speed of x at time t,
$t_1 \prec t_2$ denotes that t_1 is temporally before t_2.

C1 deals with the movement of k wrt $RL\perp 1$ at t (distance constraint):

–: k is moving towards l: $\exists t_1\ (t_1 \prec t \wedge \forall\, t^-\ (t_1 \prec t^- \prec t\ \rightarrow\ d(k|t^-, l|t) > d(k|t, l|t))) \wedge$
$\exists t_2\ (t \prec t_2 \wedge \forall\, t^+\ (t \prec t^+ \prec t_2\ \rightarrow\ d(k|t, l|t) > d(k|t^+, l|t)))$

+: k is moving away from l: $\exists t_1\ (t_1 \prec t \wedge \forall\, t^-\ (t_1 \prec t^- \prec t\ \rightarrow\ d(k|t^-, l|t) < d(k|t, l|t))) \wedge$
$\exists t_2\ (t \prec t_2 \wedge \forall\, t^+\ (t \prec t^+ \prec t_2\ \rightarrow\ d(k|t, l|t) < d(k|t^+, l|t)))$

0: k is stable with respect to l: all other cases.

C2 deals with the movement of l wrt $RL\perp 2$ at t (cf. C1, but with k and l interchanged).

C3 has to do with the movement of k wrt RL_{kl} at t (side constraint). More formally,

–: k is moving to the left side of RL_{kl}: $\exists t_1$ ($t_1 < t \wedge \forall\, t^-$ ($t_1 < t^- < t \rightarrow$ k is on the right side of RL_{kl} at t)) $\wedge\, \exists t_2$ ($t < t_2 \wedge \forall\, t^+$ ($t < t^+ < t_2 \rightarrow k$ is on the left side of RL_{kl} at t))
+: k is moving to the right side of RL_{kl}: $\exists t_1$ ($t_1 < t \wedge \forall\, t^-$ ($t_1 < t^- < t \rightarrow k$ is on the left side of RL_{kl} at t)) $\wedge\, \exists t_2$ ($t < t_2 \wedge \forall\, t^+$ ($t < t^+ < t_2 \rightarrow k$ is on the right side of RL_{kl} at t))
0: k is moving along RL_{kl}: all other cases.
C4 describes the movement of l wrt the RL_{lk} at t (cf. C3, but with k and l interchanged).

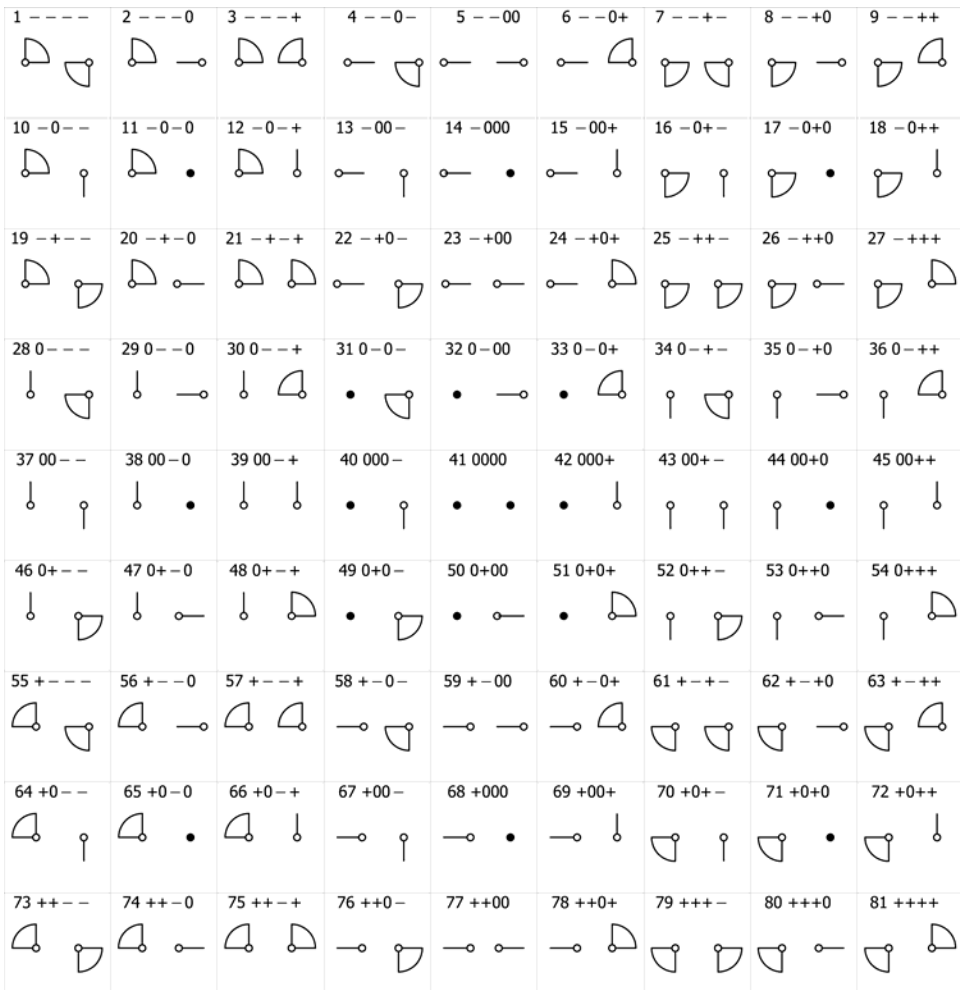

Fig. 2. QTC_C relation icons.

We can now represent a QTC_C relation by a label consisting of 4 characters. Each of the 81 relations can be represented by a relation icon (Fig. 2). The left and right dot of a relation icon respectivelly represents the position of *k* and *l*. A dot is filled if the object can be stationary, and open if the object cannot be stationary. The disk quarters are, topologically speaking, open; for relation (– – – 0) in Fig. 2: the movement of *k* can be from *k* to every point on the curved part of the quarter part excluding the horizontal and the vertical line segment, the movement of *l* can only be from *l* straight to *k*, which is along the line drawn from the open right dot.

2.2 QTC_C for Multiple Temporal Primitives and Multiple Spatial Entities

There are two *temporal primitives* over which QTC_C relations may hold: intervals (i_i) and instantaneous time points (t_i). A study period containing real world events mostly consists of a sequence of multiple QTC_C relations. Such a sequence of QTC_C relations, following the constraints imposed by the concept of continuity, is called a *conceptual animation*. '*Continuity is a formal way of enforcing the intuition that things change smoothly. A simple consequence of continuity, respected by all systems of qualitative physics, is that, in changing, a quantity must pass through all intermediate values. That is, if $A < B$ at time t_1, then it cannot be the case that at some later time t_2 $A > B$ holds, unless there was some time t_3 between t_1 and t_2 such that $A = B$*' ([18], p.25).

The interaction between multiple objects can be represented via a *QTC_C matrix* (Table 1). When working with multiple objects during a longer period, a QTC_C matrix will be created for each temporal primitive, which means that every temporal primitive is labelled with n^2 QTC_C labels (n denotes the number of objects). As a result, there will be an explosion of data that needs to be handled. However, some compression rules (CR), resulting in data-reduction without information loss, can be used:

CR1. We can reduce the number of elements from n^2 to $(n^2 – n)/2$, since only the upper part of the matrix (bold in Table 1) has to be considered. The diagonal stands for the relation of each object with itself, which gives no information. The lower part is the inverse of the upper part, thus giving redundant information.

CR2. We only need to store data when a relation, i.e. a QTC_C relation, changes.

CR3. Research has been done in simplifying topological [19] and temporal [20] relations. One could combine both in order to simplify spatio-temporal relations, i.e. QTC_C relations.

Table 1. QTCC matrix for multiple objects at one time point.

	k	*l*	*m*	*n*
k	R(k,k)	**R(k,l)**	**R(k,m)**	**R(k,n)**
l	R(l,k)	R(l,l)	**R(l,m)**	**R(l,n)**
m	R(m,k)	R(m,l)	R(m,m)	**R(m,n)**
n	R(n,k)	R(n,l)	R(n,m)	R(n,n)

CR1 is straightforward. CR3 needs an extensive research and is reserved for future research. CR2 will be studied in detail in the next section.

3 Conversion between Data Stored Using Current (Quantitative) Techniques and QTC_C

3.1 The Need to Transform Quantitative Intervals into QTC_C Intervals

A motion can be represented by a trajectory, which is a connected nonbranching continuous line having a certain shape and direction [21]. However, due to the sampling procedure of the tracking device and the need to translate the motion in a form suitable for storage and analysis in information systems, the essential characteristics of an observed track have to be represented in a discrete form [22]. Mostly, current observation-based systems capture data in an ordered sequence at regular intervals. The movement in-between these time stamps, is considered as having constant speed and direction, meaning that an intermediary time stamp can be represented via linear interpolation techniques, or in other words that the trajectories are represented by straight polylines.

Since Moving Object Databases soon will be ubiquitous, the need for conceptual models and management systems about continuously time-varying location data are vital [23]. It has been proved that humans' interaction with real life as well as humans' interaction with information systems benefits from qualitative approaches. It is thus worthwhile to find out whether it is possible to transform from quantitative data (x, y, t) into QTC_C relations. Ones this has been elaborated, it becomes straightforward to store and analyse moving objects by means of QTC_C. Thus, in order to be able to answer to CR2, the potential for conversion between data stored using quantitative techniques and QTC_C needs to be further studied. In other words, in order to store data of moving objects in QTC_C, we need a transformation of the data from (x, y, t) into QTC_C relations. How this is accomplished is explained by means of an example in the next section.

3.2 Transformation of Quantitative Spatio-Temporal Data into QTC_C Relations

In this section, transformation of quantitative spatio-temporal data into *QTC_C intervals*[1] is shown for an example representing the movement of 4 point objects (k, l, m, and n) during a study period of 30 seconds. At regular intervals (t_{0s} = time point after 0 seconds, t_{10s}, t_{20s}, and t_{30s}), the coordinates of these objects were registered in a local reference system (Table 2). We assume that the movement inbetween these time points (i.e. during the *storage intervals*) may be considered as having constant speed and constant direction (Fig. 3). In order to have full *QTC_C detail*, we need to check whether every storage interval consists of just one QTC_C relation, and whether the whole evolution for each object pair fulfils the constraints imposed by continuity.

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[1] A *QTC_C interval* is an interval consisting of one QTC_C relation, which would always get multiple QTC_C relations after extending the interval.

Table 2. (x,y)-coordinates multiple point objects moving in 2D

	t_0	t_{10}	t_{20}	t_{30}
k	(48.0;30.0)	(48.0;30.0)	(28.0;18.0)	(18.0;12.0)
l	(58.0;36.0)	(50.0;10.0)	(26.0;2.0)	(16.0;2.0)
m	(54.0;38.0)	(42.0;34.0)	(18.0;26.0)	(14.0;16.5)
n	(30.0;38.0)	(12.0;36.0)	(6.0;22.0)	(2.0;12.5)

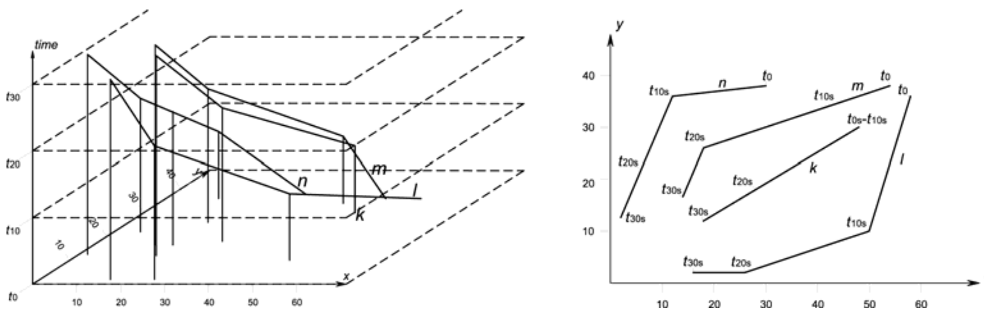

Fig. 3. Multiple objects moving in 2D: (a) space-time cube; (b) 2D representation.

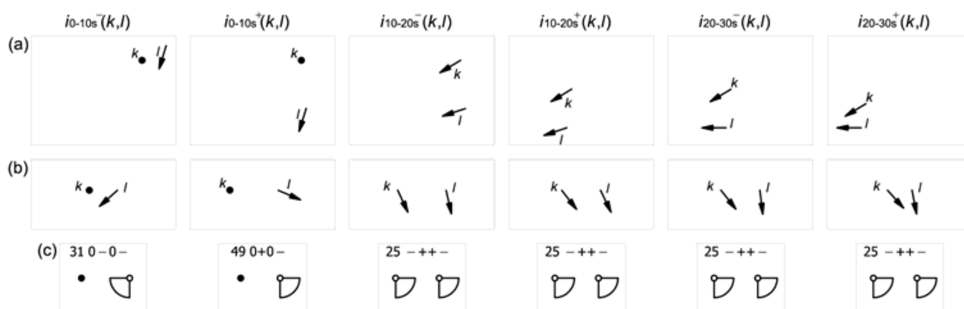

Fig. 4. Extraction of QTCC relations.

A first indication can be obtained by comparing, for each storage interval (i), whether its beginning (i^-) and end (i^+) have the same QTC_C relation. If not, this means that there has to be at least one change in QTC_C relation at a moment during this storage interval. Let us start by zooming in on the relative movement between *k* and *l* at the beginning and end of every storage interval. Fig. 4(a) shows the movements of *k* and *l* and how they were presented in the overall view of movements (Fig. 3). Fig. 4(b) shows an *oriented zoom* on each specific movement, oriented in a way that it becomes straightforward to find the QTC_C relations between objects *k* and *l* (Fig. 4(c)). One can see changes between $i_{0\text{-}10s}^-$ and $i_{0\text{-}10s}^+$, and between $i_{0\text{-}10s}^+$ and $i_{10\text{-}20s}^-$: $i_{0\text{-}10s}^-(k,l)(0 - 0 -)$; $i_{0\text{-}10s}^+(k,l)(0 + 0 -)$; $i_{10\text{-}20s}^-(k,l)(- + + -)$; $i_{10\text{-}20s}^+(k,l)(- + + -)$; $i_{20\text{-}30s}^-(k,l)(- + + -)$; $i_{20\text{-}30s}^+(k,l)(- + + -)$.
Studying the object pairs ((*k*, *m*), (*k*,*n*), (*l*,*m*), (*l*,*n*), (*m*,*n*)) gives the QTC_C matrices presented in Table 3, resulting in the changes for:
(*k*,*m*): between $i_{0\text{-}10s}^-$ and $i_{0\text{-}10s}^+$, between $i_{0\text{-}10s}^+$ and $i_{10\text{-}20s}^-$, and between $i_{10\text{-}20s}^+$ and $i_{20\text{-}30s}^-$;

(k,n): between $i_{0\text{-}10s}^{+}$ and $i_{10\text{-}20s}^{-}$;
(l,m): between $i_{0\text{-}10s}^{+}$ and $i_{10\text{-}20s}^{-}$, and between $i_{10\text{-}20s}^{+}$ and $i_{20\text{-}30s}^{-}$;
(l,n): between $i_{0\text{-}10s}^{-}$ and $i_{0\text{-}10s}^{+}$, and between $i_{0\text{-}10s}^{+}$ and $i_{10\text{-}20s}^{-}$;
(m,n): nothing.

Table 3. QTC_C-relations for multiple point objects moving in 2D.

$i_{0\text{-}10s}^{-}$	l	m	n
k	0 – 0 –	0 – 0 +	0 + 0 +
l		+ + – +	– + – +
m			– + – +

$i_{0\text{-}10s}^{+}$	l	m	n
k	0 + 0 –	0 + 0 +	0 + 0 +
l		+ 0 – +	+ + – +
m			– + – +

$i_{10\text{-}20s}^{-}$	l	m	n
k	– + + –	0 + 0 +	– + – +
l		0 0 – +	– – – +
m			– + – +

$i_{10\text{-}20s}^{+}$	l	m	n
k	– + + –	– + – +	– + – +
l		0 0 – +	– – – +
m			– + – +

$i_{20\text{-}30s}^{-}$	l	m	n
k	– + + –	– – – +	– + – +
l		– – – +	– – – +
m			– + – +

$i_{20\text{-}30s}^{+}$	l	m	n
k	– + + –	– – – +	– + – +
l		– – – +	– – – +
m			– + – +

There are two major categories (Cat) of changes that can be detected. A difference between:
- the relation at the end of the previous and the beginning of the next interval (Cat1)
$i_{0\text{-}10s}^{+}(k,l)(0+0-)$ to $i_{10\text{-}20s}^{-}(k,l)(-++-)$; $i_{0\text{-}10s}^{+}(k,m)(0+0+)$ to $i_{10\text{-}20s}^{-}(k,m)(-+-+)$; $i_{10\text{-}20s}^{+}(k,m)(-+-+)$ to $i_{20\text{-}30s}^{-}(k,m)(---+)$; $i_{0\text{-}10s}^{+}(k,n)(0+0+)$ to $i_{10\text{-}20s}^{-}(k,n)(-+-+)$; $i_{0\text{-}10s}^{+}(l,m)(++-+)$ to $i_{10\text{-}20s}^{-}(l,m)(00-+)$; $i_{10\text{-}20s}^{+}(l,m)(00-+)$ to $i_{20\text{-}30s}^{-}(l,m)(---+)$; $i_{0\text{-}10s}^{+}(l,n)(++-+)$ to $i_{10\text{-}20s}^{-}(l,n)(---+)$.
- the relation at the beginning of the current and the end of the current interval (Cat2)
$i_{0\text{-}10s}^{-}(k,l)(0-0-)$ to $i_{0\text{-}10s}^{+}(k,l)(0+0-)$; $i_{0\text{-}10s}^{-}(k,m)(0-0+)$ to $i_{0\text{-}10s}^{+}(k,m)(0+0+)$; $i_{0\text{-}10s}^{-}(l,n)(-+-+)$ to $i_{0\text{-}10s}^{+}(l,n)(++-+)$.
According to the theory of dominance [24]) an interval-like qualitative value (+ or – in QTC_C) will reach a landmark value (0 in QTC_C) at a time instant. Now, let us analyse the example1 of Cat1: from $i_{0\text{-}10s}^{+}(k,l)(0+0-)$ to $i_{10\text{-}20s}^{-}(k,l)(-++-)$; char1 changes from 0 to – and char3 changes from 0 to +. This means that at the time point where both intervals meet (t_{10s}), the char1 and char3 need to be 0, resulting in $t_{10s}(k,l)(0+0-)$. Analogous reasoning applies to:
$i_{0\text{-}10s}^{+}(k,m)(0+0+)$ to $i_{10\text{-}20s}^{-}(k,m)(-+-+)$ gives $t_{10s}(k,m)(0+0+)$;
$i_{0\text{-}10s}^{+}(k,n)(0+0+)$ to $i_{10\text{-}20s}^{-}(k,n)(-+-+)$ gives $t_{10s}(k,n)(0+0+)$;
$i_{0\text{-}10s}^{+}(l,m)(++-+)$ to $i_{10\text{-}20s}^{-}(l,m)(00-+)$ gives $t_{10s}(l,m)(00-+)$;
$i_{10\text{-}20s}^{+}(l,m)(00-+)$ to $i_{20\text{-}30s}^{-}(l,m)(---+)$ gives $t_{10s}(l,m)(00-+)$.
Because continuity constrains the kinds of changes that are possible, a direct change from – to + and vice versa is impossible, since such a change must pass the qualitative value 0. This landmark value 0 only needs to hold for an instant [24]. Now, let us consider the remaining cases of the first category of changes. Let us analyse: from $i_{10\text{-}20s}^{+}(k,m)(-+-+)$ to $i_{20\text{-}30s}^{-}(k,m)(---+)$. Char2 changes from + to –. This means that at the time point where both intervals meet (t_{20s}), char2 needs to be 0, resulting in: $t_{20s}(k,l)(-0-+)$. Analogous reasoning: $i_{0\text{-}10s}^{+}(l,n)(++-+)$ to $i_{10\text{-}20s}^{-}(l,n)(---+)$ gives $i_{10s}(l,n)(00-+)$.

After analysing the first category of changes, one can generate the QTC_C matrices for all the time stamps t_{0s}, t_{10s}, t_{20s}, and t_{30s} (Table 4).

Table 4. QTC_C relations for multiple point objects moving in 2D.

t_{0s}	*l*	*m*	*n*
k	0 – 0 –	0 – 0 +	0 + 0 +
l		+ + – +	– + – +
m			– + – +

t_{10s}	*l*	*m*	*n*
k	0 + 0 –	0 + 0 +	0 + 0 +
l		0 0 – +	0 0 – +
m			– + – +

t_{20s}	*l*	*m*	*n*
k	– + + –	– 0 – +	– + – +
l		0 0 – +	– – – +
m			– + – +

t_{30s}	*l*	*m*	*n*
k	– + + –	– – – +	– + – +
l		– – – +	– – – +
m			– + – +

In the second category of changes, new time points need to be inserted to present QTC_C events. The only interval of the example that needs a further subdivision is $i_{0\text{-}10s}$. Three cases need to be studied in order to see where the further subdivision needs to be time snapped: (*k*,*l*), (*k*,*m*) and (*l*,*n*). The situations are analysed in Fig. 5. Let us start with situation 1: $i_{0\text{-}10s}(k,l)$. Comparing char2 of $i_{0\text{-}10s}^{-}(k,l)(0\ –0\ –)$ and $i_{0\text{-}10s}^{+}(k,l)(0\ +0\ –)$, implies that the interval needs a subdivision. Alternatively, based on the double-cross dichotomy, the movement of $l|i_{0\text{-}10s}^{-}$ with respect to $lk|i_{0\text{-}10s}^{-}$ is front-left, and the movement of $l|i_{0\text{-}10s}^{+}$ with respect to $lk|i_{0\text{-}10s}^{+}$ is back-left. Since a landmark needs to be passed in order to have a continuous evolution, the storage interval needs further subdivision, i.e., the velocity vector *l* needs to pass left. The question now is where this landmark is situated. The division process for $i_{0\text{-}10s}(k,l)$ is as follows (Fig. 5(a)):

Step 1: draw the movements of *k* and *l* during $i_{0\text{-}10s}$, together with $lk|i_{0\text{-}10s}^{-}$ and $lk|i_{0\text{-}10s}^{+}$

Step 2: draw *lk* at the middle of $i_{0\text{-}10s}$, which is $lk|t_{5s}$.

The movement of $l|t_{5s}$ with respect to $lk|t_{5s}$ is back-left.

Thus, the change occurs between $i_{0\text{-}10s}^{-}$ and t_{5s}. So: new interval is $i_{0\text{-}5s}$

Step 3:

Repeat Step 1 and Step 2 for the new interval until the movement of *l* with respect to *lk* is 90° (or until the difference between the movement of *l* with respect to *lk* and 90° is less than a specified threshold). In the presented case, we need to iterate until step 7, where this point is reached at 32% of $i_{0\text{-}10s}$ giving the landmark value at $t_{3.2s}$.

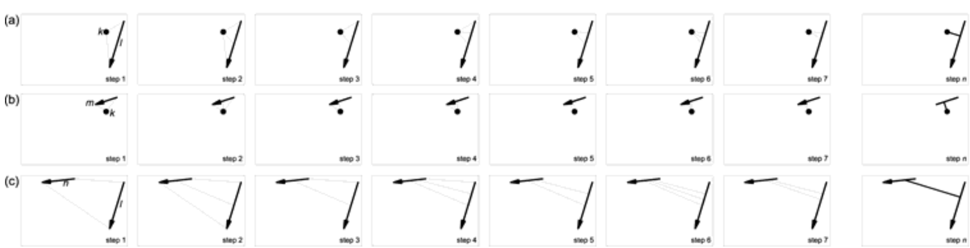

Fig. 5. Subdivision of QTC intervals: (a) i0-10s(k,l); (b) i0-10s(k,m); (c) i0-10s(l,n).

One can also generate the division process for $i_{0\text{-}10s}(k,m)$ (Fig. 5(b)) resulting in a change after 65% of $i_{0\text{-}10s}$ giving a landmark value at $t_{6.5s}$ and the division process for $i_{0\text{-}10s}(l,n)$ (Fig. 5(c)) giving a change after 32% of $i_{0\text{-}10s}$, being simultaneous to the change of (*k*,*l*). Thus $i_{0\text{-}10s}$ will be subdivided in: $i_{0\text{-}3.2s}$, $t_{3.2}$, $i_{3.2\text{-}6.5s}$, $i_{6.5}$, and $i_{6.5\text{-}10s}$. Since the other object pairs do not change during $i_{0\text{-}10s}$, the following changes are the only ones that need to be studied in order to get QTC_C matrices for $i_{0\text{-}3.2s}$, $t_{3.2}$, $i_{3.2\text{-}6.5s}$, $i_{6.5}$, and $i_{6.5\text{-}10s}$:

$i_{0\text{-}10s}^{-}(k,l)(0 - 0 -)$ thus $i_{0\text{-}3.2s}(k,l)(0 - 0 -)$, and $i_{0\text{-}10s}^{+}(k,l)(0 + 0 -)$ thus $i_{3.2\text{-}10s}(l,k)(0 + 0 -)$. Thus (cf. category 2 changes) $t_{3.2}(k,l)(0\ 0\ 0 -)$.

$i_{0\text{-}10s}^{-}(k,m)(0 - 0 +)$thus $i_{0\text{-}6.5s}(k,m)(0 - 0 +)$,and $i_{0\text{-}10s}^{+}(k,m)(0 + 0 +)$thus $i_{6.5\text{-}10s}(k,m)(0 + 0 +)$. Thus (cf. category 2 changes) $t_{6.5}(k,m)(0\ 0\ 0 +)$.

$i_{0\text{-}10s}^{-}(l,n)(- + - +)$ thus $i_{0\text{-}3.2s}(l,n)(- + - +)$, and $i_{0\text{-}10s}^{+}(l,n)(+ + - +)$ thus $i_{3.2\text{-}10s}(l,n)(+ + - +)$. Thus (cf. category 2 changes) $t_{3.2}(l,n)(0 + - +)$.

Finally, one gets the whole configuration of the interactions between the 4 objects during the period of 30 seconds; Fig. 6 and Table 5 give a general overview. A compressed version (no information loss + redundant information deleted) can be written as follows:

(k,l): $t_{0s}(0 - 0 -)$, $t_{3.2s}(0\ 0\ 0 -)$, $i_{3.2\text{-}6.5s}(0 + 0 -)$, $i_{10\text{-}20s}(- + + -)$, $t_{30s}(- + + -)$;
(k,m): $t_{0s}(0 - 0 +)$, $t_{6.5s}(0\ 0\ 0 +)$, $i_{10\text{-}20s}(- + - +)$, $t_{20s}(- 0 - +)$, $i_{20\text{-}30s}(- - - +)$, $t_{30s}(- - - +)$;
(k,n): $t_{0s}(0 + 0 +)$, $i_{10\text{-}20s}(- + - +)$, $t_{30s}(- + - +)$;
(l,m): $t_{0s}(+ + - +)$, $i_{6.5\text{-}10s}(0 + 0 +)$, $t_{10s}(0\ 0 - +)$, $i_{20\text{-}30s}(- - - +)$, $t_{30s}(- - - +)$;
(l,n): $t_{0s}(- + - +)$, $t_{3.2s}(0 + - +)$, $i_{3.2\text{-}6.5s}(+ + - +)$, $t_{10s}(0\ 0 - +)$, $i_{10\text{-}20s}(- - - +)$, $t_{30s}(- - - +)$;
(m,n): $t_{0s}(- + - +)$, $t_{30s}(- + - +)$.

Table 5. QTCC relations for multiple point objects moving in 2D.

t_{0s}	l	m	n
k	0 – 0 –	0 – 0 +	0 + 0 +
l		+ + – +	– + – +
m			– + – +

$i_{0\text{-}3.2s}$	l	m	n
k	0 – 0 –	0 – 0 +	0 + 0 +
l		+ + – +	– + – +
m			– + – +

$t_{3.2}$	l	m	n
k	0 0 0 –	0 – 0 +	0 + 0 +
l		+ + – +	0 + – +
m			– + – +

$i_{3.2\text{-}6.5s}$	l	m	n
k	0 + 0 –	0 – 0 +	0 + 0 +
l		+ + – +	+ + – +
m			– + – +

$t_{6.5s}$	l	m	n
k	0 + 0 –	0 0 0 +	0 + 0 +
l		+ + – +	+ + – +
m			– + – +

$i_{6.5\text{-}10s}$	l	m	n
k	0 + 0 –	0 + 0 +	0 + 0 +
l		+ + – +	+ + – +
m			– + – +

t_{10s}	l	m	n
k	0 + 0 –	0 + 0 +	0 + 0 +
l		0 0 – +	0 0 – +
m			– + – +

$i_{10\text{-}20s}$	l	m	n
k	– + + –	– + – +	– + – +
l		0 0 – +	– – – +
m			– + – +

t_{20s}	l	m	n
k	– + + –	– 0 – +	– + – +
l		0 0 – +	– – – +
m			– + – +

$i_{20\text{-}30s}$	l	m	n
k	– + + –	– – – +	– + – +
l		– – – +	– – – +
m			– + – +

t_{30s}	l	m	n
k	– + + –	– – – +	– + – +
l		– – – +	– – – +
m			– + – +

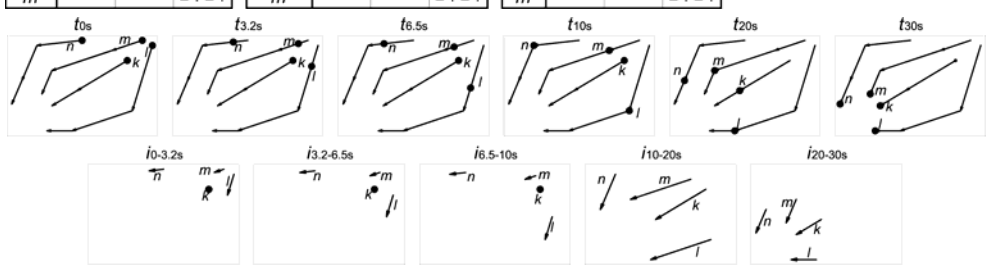

Fig. 6. Multiple point objects moving in 2D.

4. Outlook

At first sight, the amount of QTC_C data that needs to be stored is huge. However, one can see that the storage for quantitative data needs 2 real numbers (respectively for the *x*- and *y*-coordinate) for each temporal primitive that changes, being 4 bytes = 32 bit per number when taking single-precision floating-point.[2] The storage for QTC_C only needs 3 possible (qualitative) values that can be stored in a 2-bit word, per character. Each QTC_C relation needs 7 bits. The amount of data that needs to be stored when working in QTC_C is thus not significantly or exponentially more than if one works with quantitative data.

The presented work builds on the basis for an intelligent temporal GIS, being able to answer complex spatio-temporal queries concerning moving objects, i.e. analysing of and reasoning with complex relations between moving objects. In the near future, the different sorts of spatio-temporal queries (different types of spatio-temporal queries are studied in [23]) need to be studied in order to find out which sorts of queries prefer a quantitative strategy and which ones prefer a qualitative strategy (at level 1 or level 2). Be aware that if storing the information in QTC_C it is not possible to go back to (x, y, z). More important of course is that interesting spatio-temporal queries concerning moving objects and their interactions can be queried to the system without the need to do additional calculations. One could therefore question whether both the quantitative and the qualitative system are complementary and whether therefore the most interesting way to store this kind of data is in a hybrid system.

In [13], QTC_C has been extended to a second level by adding char5 and char6; char5 standing for the relative speed and char6 giving a qualitative measure for the relative direction of the velocity vector with respect to the reference line between *k* and *l*. At this second level, the speed and the angular constraints also can be considered. The subdivision process based on these characters will be studied in further research. This will result in a more profound subdivision from quantitative to QTC_C information.

On the one hand, further fundamental research has to be done in finding out the complexity, the update possibilities, and the simulation possibilities of the approach. On the other hand, more meaningful examples need to be worked out in order to illustrate the applicability and naturalness of the proposed approach.

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[2] Single-precision floating-point standing for numbers between -3.402823E3 and -1.40129E-45 for negative values, and 1.40129E-45 and 3.40282E38 for positive values.

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