Triggers and Continuous Queries in Moving Objects Databases

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Abstract

This work addresses the problem of maintaining the consistency of the answers to continuous queries which are posed by the users of the Moving Objects Databases (MOD). We propose a framework which enables detecting and processing the pending queries whose answers need to be re-evaluated upon modifications to the MOD. Relevant syntactic elements of the user’s queries and their semantic implications are identified, and the basic components of a system that can be used for this task are specified. We show how triggers can be used to maintain the answers to the users’ queries “up to date” with respect to the modifications to the MOD and we demonstrate that our system can be implemented on top of the existing ORDBMS.

Keywords: Moving Objects Databases, Continuous Queries, Triggers.

1 Introduction and Motivation

A wide range of applications (traffic control, transportation industry, digital battlefields, environment monitoring, dynamic resource discovery, ...) need some form of a management of the location information [12]. The ability to store and process information about moving objects has spurred a lot of recent scientific research, where the subject is termed Moving Objects Databases (MOD) [23, 1, 14]. On the other hand, there is a bulk of work that has been done in the field of Active Database Systems. The seemingly straightforward event-condition-action paradigm, which adds a reactive behavior to the database systems, has been investigated from many aspects [5, 22]; and prototype systems have been implemented (e.g. STARBURST [21], Chimera [3]). Due to the recent trend for supporting universal applications, commercial Object-Relational Database Management Systems (ORDBMS) are now offering new (application-specific) complex data types; inheritance; user-defined routines which implement operators/methods over the user-defined types; extensions to SQL ([8]), predicates (e.g. intersects, contains) and functions for spatial calculations (e.g. distance).

The above observations point out a strong existing body of work which, so far, seems uncorrelated. In this paper we tackle an important problem in the MOD using active rules (triggers) and we demonstrate that the proposed framework can be implemented using the existing ORDBMS.

1.1 Problem Description and Our Contributions

Consider a MOD which stores the information about the trajectories of (a set of) moving objects. The MOST model in [15], identified three categories of queries: – instantaneous, for which the answer is evaluated immediately and transmitted to the user; – continuous, which need to be evaluated at every “clock-tick” so that the consistency of their answer is ensured; – persistent, which not only need to be evaluated at each time instance, but may also require evaluation over an unbounded history.

In this work we focus on continuous queries like, for example Q1: “Retrieve all the vehicles which will be no further than 0.3 miles from me, between 8:00PM and 8:10PM”. If the query was posed at 6:30PM, it becomes continuous one, because many modifications to the MOD can occur between the time Q1 was posed and the relevant time-interval for its answer. For example, one of the cars that was part of the answer to Q1 changed its motion plan at 7:45PM. Not all the modifications to the MOD may be relevant to Q1, e.g. an accident at 7:30PM, on a road segment which affects no vehicle that is part of the answer of Q1.
Our goal is to maintain the information about pending continuous queries to the MOD and avoid re-evaluation of their answers when it is not necessary, under the standard modifications: Updates, Deletions and Insertions. The main contributions of this work are:

- We identify the relevant syntactic elements of the users' continuous queries and their semantic impacts.
- We propose a framework which can be used to detect the set of queries whose answers are affected by the modifications to the MOD.
- We describe the specifications of the triggers which enable the MOD to properly react to the modifications (and avoid re-evaluation of continuous queries when not needed).

2 Preliminary Background

In this section we briefly introduce the model of the trajectory and its construction, and the issues related to the modifications of the MOD.

2.1 Trajectory Model and Updates

In order to capture the spatio-temporal nature of a given moving object, we need to, somehow, represent its motion. This information pertains to the object's whereabouts at a given time instance - (location, time), and is represented using a trajectory [18]:

- A trajectory of a moving object is a piece-wise linear function \( f : T \to (x,y) \), represented as a sequence of points \((x_1,y_1,t_1), (x_2,y_2,t_2), \ldots, (x_n,y_n,t_n)\) \((t_1 < t_2 < \ldots < t_n)\). For a given a trajectory \( T_r \), its projection on the X-Y plane is called the route of \( T_r \).

The object is at \((x_i,y_i)\) at time \(t_i\), and during each segment \([t_i, t_{i+1}]\), it moves along a straight line from \((x_i,y_i)\) to \((x_{i+1},y_{i+1})\), and at a constant speed. The expected location of the object at any time \( t \in [t_i, t_{i+1}] \) \((1 \leq i < n)\) is obtained by a linear interpolation.

Relative to now, a trajectory can represent both the past and the future motion of objects. The future motion plan is constructed by using electronic maps\(^1\) and the speed profiles information, which are input to the time-dependent shortest path algorithm [4] (see [18] for details). For the past motion of the object(s), one can use a set of 3D points \((x_1,y_1,t_1), (x_2,y_2,t_2), \ldots, (x_n,y_n,t_n)\), generated by the on-board GPS, which were transmitted by a moving object periodically. The points are "snapped" on the map, and then connected with the time-dependent shortest path.

This model of a trajectory can be represented as a User-Defined Type (UDT) in an ORDBMS. trajectory is a row type LIST of point, which is another row type having \(x,y\) and \(t\) attributes:

\[
\text{MOT}(\text{oid, trajectory, \ldots other static attributes})
\]

In the rest of this paper, MOT denotes the table which stores the moving object trajectories and MOD denotes the moving objects database.

2.2 Modifications to the MOT

There are few sources which can cause modifications to the MOT, that we consider:

1. **insert** – At any time instance, a new trajectory may be inserted in the database, which is assigned a unique oid.

2. **delete** – An existing trajectory of a given moving object (given oid) may be deleted from the MOT.

3. **update** – There are two basic sources of updating a trajectory:

   3.1. – A given moving object may decide to change its route.

   3.2. – There may be some unforeseen variations to the speed profiles used for constructing a future trajectory: accidents; road-works; bad weather; etc... In this case, the MOD server needs to utilize some sort of a real-time information to keep the (location-time) information accurate\(^2\). The details of identifying the trajectories affected by traffic incidents and their updates are presented in [17].

3 Classification of MOD Queries

In this section we analyze the important aspects of the requests that a user can pose to the MOD. We identify the significant time-aspects as syntactic elements in the queries, as well as the categories of queries.

We distinguish between two continuous Query Requests (QR) to the MOD: 1. Query Requesting Notification (QRN) in which the user basically requests from the MOD to notify her/him when certain event occurs/ certain condition becomes true, like \( QRN_1 \) : "Notify me when I am within 2 miles from hospital, between 1PM and 3PM". 2. Query Requesting Answer (QRA) in which an answer-set needs to be transmitted to the user. For example, \( QRA_1 \) : "Retrieve the motels that will be no further then 1 mile from my route, between 9PM and 10PM".

3.1 Significant Times of the Requests

There are three significant time-instances pertaining to a given QR:

\(^1\)Like, for example, the ones of Geographic Data Technology.

\(^2\)For example, (www.at.uci.edu) maintains the current traffic information for the expressways around Chicagoland.
• **Time Posed** - $t_p$, which is the time at which the QR is sent to the MOD.
• **Time to Answer** - $t_a$, which is the time at which the user wants the answer-set transmitted. For example, the user may pose a $QRA_2$ at 4PM: “Retrieve all the motels that will be no further than 1 mile from my route, between 9PM and 10PM, and send me the answer at 6PM” ($t_a = 6PM$).
• **Termination Time** - $t_t$, which is the time after which the QR is no longer valid. In the context of $QRA_2$ above, this time is $t_t = 10PM$.

### 3.2 Categories of Queries

Now we present the categories of queries which can be used in a QR. We do not address here the issues of their linguistic constructs or processing [14, 18].

- **Location Queries**: These queries pertain to the objects’ whereabouts and time. We consider two variants:
  1. $\text{Where\_at}(t, oid)$ - returns the expected location (i.e., the $(x, y)$ coordinates) of the object $oid$ at time $t$.
  2. $\text{When\_at}(x, y, oid)$ - returns the time at which the object $oid$ is expected to be at location $(x, y)$.
- **Range Queries**: These spatiotemporal queries return the set of moving objects which are within a given (static) region, for a given time-interval. The basic syntax is $\text{Inside}(R, t_1, t_2)$.
- **Within\_Distance Queries**: These queries have a $\text{query\_objects}$ as one parameter and return a set of $\text{answer\_objects}$ (syntax is $\text{Within\_Distance(obj, t_1, t_2)$}

Based on the the nature (Dynamic or Static) of the $\text{query\_object}$ and the $\text{answer\_objects}$, one can have for variants of this type of query: $\text{DD, DS, SD and SS}$ (a spatial query).

- **k-Nearest\_Neighbour (k-NN) Queries**: With the standard semantics - return the $k$ nearest objects to a given object and, again with the 4 variants.

### 4 Basic Components

In this section we define the basic architecture which is needed to maintain the information about queries posed to the MOD and to properly update it upon modifications to the MOT.

#### 4.1 Schemas

We extend the MOT schema, introduced in Section 2, with two more attributes - $\text{Pending\ Posed\ Queries (ppq)}$ and $\text{Part\ of\ Query\ Answer (pqa)}$. Both of the new attributes serve as flags: $\text{ppq}$ of the object $oid_i$ is 0 if and only if there is no query posed by $oid_i$ which is still “pending”. Otherwise, the value of the $\text{pqa}$ is the number of pending queries posed by the object $oid_i$; the $\text{ppq}$ for a given $oid_i$ is 0 iff there are no queries (posed by a mobile or web-based user) for which $oid_i$ is part of their answer-set. $\text{pqa} = n$ denotes that the given $oid$ is part of the answers for $n$ different queries.

We have two more relations$^3$, $\text{Issued}$ and $\text{PartAnswer}$ with their respective schemas:

- $\text{Issued} (\text{User\_id}, \text{Query\_id}, \text{Terminate})$ and $\text{PartAnswer} (\text{Query\_id}, \text{Object\_id})$.

The first relation keeps track of which user (recall that we can have web-based users) issued a particular query, and its $t_a$ parameter. The second one maintains the information about objects which are part of the answer for a given query.

#### 4.2 Scripts

We have several PL/SQL (or, equivalently, Embedded SQL) scripts:

1. $\text{Transmit\Answer (Q, U)}$ is used to transmit the answer of the query $Q$ to the user $U$, who posed it. It extracts the $t_a$ parameter of a given query $qid$. $\text{SELECTs}$ all the $\text{Object\_id}$ FROM the $\text{PartAnswer}$ WHERE $\text{PartAnswer.Query\_id} = \text{qid}$ and send them to the $uid$.

2. $\text{Receive (U, Q)}$, upon receiving the query $Q$ from the user $U$ ($uid$) assigns a unique $qid$ to $Q$; and inserts the tuple ($uid, qid, t$) into the table $\text{Issued}$. If $uid$ is a mobile user, it also increments by one the value of its $\text{ppq}$ attribute in the $\text{MOT}$. Then, it invokes the script $\text{Eval(qid)}$ (see below) and creates an instance of the script $\text{Transmit\Answer(qid, uid)}$.

3. $\text{Eval(Q)}$, basically evaluates a query $qid$. It properly updates the $\text{PartAnswer}$ table with all the $\text{(qid, oid)}$ tuples, where $oid$ is an element of the answer-set for $Q$. If this was the first invocation of $\text{Eval(Q)}$ (i.e., $\text{PartAnswer(query\_id, object\_id)}$ did not have any tuples with $qid$), then the value for the $\text{pqa}$ attribute of each $oid$ in the $\text{MOT}$ table is incremented by one. Otherwise: - if the tuple ($qid, oid\_i$) was in the $\text{PartAnswer}$, but $oid\_i$ is no longer in the answer-set for $Q$, the tuple is deleted, and the $\text{pqa}$ value for $oid\_i$ in the $\text{MOT}$ is decremented by one; - if the tuple ($qid, oid\_i$) was not in the $\text{PartAnswer}$, the tuple is inserted and the $\text{pqa}$ value of the $oid\_i$ is incremented by one in the $\text{MOT}$.

4. $\text{Eval\All()}$ simply scans the $\text{Issued}$ relation and, for every query $qid$ whose $\text{Terminate}$ attribute is not less than $t_{current}$, invokes the $\text{Eval(qid)}$.

5. $\text{Eval\All\_Issued} (\text{UID})$ scans the $\text{Issued}$ relation

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$^3$We assume that the “static” data i.e., hospitals, motels, landmarks are properly represented and can be queried/accessed, say w.r.t. names and geo-coordinates.
and, for every tuple for which Issued.User_id = UID and Issued.Terminate > tcurrent, invokes Eval(Issued.Query_id). If its execution caused modifications to the PartAnswer and there is an existing instance of the script TransmitAnswer(QID, UID) for which QID = Issued.Query_id, the new answer set is transmitted to the user UID.

6.) ReEval_Answer(QID) scans the relation PartAnswer, and for every tuple for which PartAnswer.Object_id = OID, it invokes the script Eval(PartAnswer.Query_id).

7.) Remove(QID) removes the tuple for which Issued.Query_id = QID; decrements the MOT.ppq counter for the respective MOT.oid = Issued.User_id (if the tuple is still in the MOT); removes every tuple from PartAnswer table for which its respective attribute PartAnswer.Query_id = QID and decrements the MOT.pqa attribute of the corresponding MOT.oid = PartAnswer.Object_id. Finally, it removes any existing instance of the TransmitAnswer(QID, UID).

8.) Purge(Issued) periodically checks the Issued table. For every tuple for which the value of the Terminate attribute is less than tcurrent, it invokes the Remove(Issued.Query_id) script.

5 Active Rules

This section describes the syntax and semantics of the respective active rules which ensure that the changes to the queries’ answers are properly considered.

5.1 Updates to the MOT

Recall that an update may be initiated by the mobile user itself or by the MOD server, when unexpected traffic conditions are detected from a real-time traffic site. To capture this, we have two triggers:

CREATE TRIGGER MOD_UPDATES_1
AFTER UPDATE OF Trajectory ON MOT
WHERE MOT.ppq > 0
Eval_All_Issued(MOT.oid) and:
CREATE TRIGGER MOD_UPDATES_2
AFTER UPDATE OF Trajectory ON MOT
WHERE MOT.pqa > 0
ReEval_Answer(MOT.oid)

The triggers are designed so that they capture both cases: the updated object has posed a query to the MOD; the updated object is part of an answer for a query posed by another object. We illustrate the behavior of the triggers with the following example, illustrated on Figure 1:

Example 1. Assume that the moving object oid4 posed the following query at 1PM: “retrieve all the objects which will be no further than 0.25 miles from me between 3:50PM and 4:00PM, and send me the answer at 3PM”, and it was assigned Query_id = qid7. When its answer was calculated, it had the objects oid6 and oid9. Now, suppose the Real-Time traffic site reported a congestion on certain road segments at 3:30 PM. The MOD will identify the affected trajectories and update them accordingly (c.f. [17]). The thicker portions of the oid5 and oid6 on Figure 1 illustrate the slow-down update. This is an event which “awakes” both triggers. Since the moving object oid6 has not posed any queries itself, the condition part of the trigger MOD_UPDATES_1 fails. However, since oid6 is part of the answer to the qid7 (posed by the oid4), the condition for the MOD_UPDATES_2 is satisfied. Thus, its action is executed, which invokes the script ReEval_Answer(qid6). The sequence of execution is illustrated by the numbers in the circles above the arrowed lines. After executing Eval(qid7) it is detected that, due to the slow-down, oid6 is no longer part of the answer set. However, the object oid5 which, initially, was moving too fast to be “...no further than 0.25 miles from me (= oid4) between 3:50PM and 4:00PM...” (c.f. specifications of qid7), now is slowed down enough so that it becomes part of the answer. Since the output generated by Eval(qid7) has changed, the new answer is transmitted to the user oid4.

5.2 Deletions to the MOT

When a certain tuple is deleted from the MOT table (e.g., the moving object has a serious engine problem and it will not be a traffic participant), again we need to consider its effects to the pending user’s queries. Any query posed by the affected object itself is no longer of interest:

CREATE TRIGGER MOD_DELETIONS_1
AFTER DELETE ON MOT
REFERENCING OLD AS OldTuple
WHERE (OldTuple.ppq > 0)
REMOVE(X) WHERE (X IN

SELECT Query_id
FROM Issued
WHERE Query_id = OldTuple.ID)

In case the deleted object either has not posed any queries itself, or the ones that it posed are already removed from the Issued table, due to the execution of the MOD_DELETIONS_1 trigger above (for which we always assign higher priority), we have:

CREATE TRIGGER MOD_DELETIONS_2
AFTER DELETE ON MOT
          REFERENCING OLD AS OldTuple
WHERE (OldTuple.pqa > 0 )
ReEval_Answer(OldTuple.ID)

In case the deleted object had both posed queries AND
was part of some other query’s answer, it is handled
by the first trigger, MOD.DELETIONS.1, and the sec-
ond trigger has no effect because all the tuples for
which PartAnswer.Object_id = OldTuple.id are al-
ready deleted.

5.3 Insertions to the MOT

An insertion of a new moving object could possibly
affect the answer set to every pending query in the MOD.
Thus, we have the following:
CREATE TRIGGER MOD.INSERTIONS, for which:
• Event: AFTER INSERT ON MOT
• Action: Eval_All()
This situation is most straightforward to specify, but
most complicated for the efficient processing of (its im-
 pact on) the pending users’ queries (brute force ap-
proach is to simply re-evaluate every query in the MOD).
The optimization problem is beyond the scope of this
work and an ongoing research topic.

6 Related Work

The topic of active databases has been extensiv-
ely studied for a long time [5, 22] (see the collec-
tion in [10] for an extensive list of references). Many aspects have
been investigated: – termination and confluence [19]; –
coupling modes between transactions which generated
events vs. condition evaluation and actions execution
[5]; – expressiveness and behavior issues [11, 2]. How-
ever, at the time when the research in the field of Active
Databases was at its peak, the research on Moving Ob-
jects Databases was barely at its infancy. Due to the
specific nature of the spatio-temporal domain, none of
the works can be applied directly to the MOD settings.

Moving Objects Databases research has attracted
a lot of attention in the recent years. Researchers have
identified and investigated several aspects: – Access
Methods: both in primal [14, 16] and in dual space
[1, 7]; – Uncertainty: its communication cost vs. im-
precision trade-off [23], and implication on the spatio-
temporal range queries [18]; – Linguistic issues and
models: modeling and querying moving objects by pre-
senting a rich algebra of operators and data types [6]
and the special case of road networks [20].

The MOST model [15] represented moving objects
as a function of (location, velocity, vector) and intro-
duced the notion of dynamic attributes and continuous
queries, which are the topic of our work. As defined,
continuous queries required re-evaluation with every
clock-tick and the algorithms use rather “esoteric” lan-
guage (FTL-based). Our advantage is that we identi-
fied the important time-parameters and the categories
of queries and, based on their semantics, proposed a
methodology which utilizes triggers to avoid evaluation
of the continuous queries with every clock-tick.

7 Concluding Remarks and Future Work

We presented a framework for evaluating continous
queries posed to the MOD. After presenting the cat-
cegories of queries and their relevant “semantic dimen-
sions”: – time instances and dynamic vs. static na-
ture of query objects and query answers, we proposed
a framework which, upon modifications to the MOD
will re-evaluate only the queries whose answer-set may
be affected by those modifications. We identified the
basic elements of the architecture (scripts and data ta-les) which can be implemented on top of the “off the
shelf” ORDBMS.

Our ongoing research is targeted towards efficient
execution of re-evaluation of the queries’ answers,
in a similar spirit to [13] and incorporating the context-
awareness in the query processing [9].

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