MONITORING AND ANALYSIS OF WATER POLLUTION USING TEMPORAL GIS

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ABSTRACT

Water pollution caused by oil spills is a typical hazard scenario in which the understanding of object movement—here that of the oil spill—may be vital for risk minimization. Oil spills do not only present a short-term local problem but may have long-term consequences with catastrophic environmental, ecological and economic damages. If imminent movements of a spill at sea can be foreseen, the necessary resources for reducing further pollution can be allocated in time. Some factors like weather condition, marine currents, ship movements, etc. will also influence the transfer of oil spills. Such factors should be taken into account in a forecasting model. Moreover, in many cases it is also important to determine the trajectory of the object followed over time.
Moving objects in general find little support in present GIS or database systems. *Ad hoc* solutions for their storage, manipulation and visualization can be concocted, but such solutions do not lend themselves well for scaling up. We envision a data processing need in the near future for the support of large collections of moving objects, and advanced manipulations on such collections. This is the background for the on-going study that we report upon here.

1 INTRODUCTION

1.1 Considerations and problem statement

Database and GIS systems are important and powerful tools for representing and analysing real life phenomena, in which the spatial dimension plays a(n important) role. Their success is based to a large extent on *data independence*, *genericity* of the data manipulation language, and *powerful output production* possibilities. Data independence is the characteristic by which internal system features (e.g., implementation of data structures) is hidden from the users, who possibly perceive ‘their’ data in ways unrelated to actual storage techniques. Genericity of the manipulation language allows to use the same language for completely different applications, and this is mainly achieved through a level of declarativeness that goes hand in hand with data independence.

Yet, there is an important class of problems that present-day database/GIS users will find hard to tackle satisfactorily with their systems. Static phenomena can be represented well in a database and/or GIS. Typically, when the state of affairs changes, these systems allow to update by overwriting the previously known state with a new state. It has been recognized for some time that old states for many domains of application hold valuable information as well, and that these should actually remain available in the system. This has led to influential research activity both in the database (4) and in the GIS (5) domains. The predominant paradigm in these efforts has always been to look at the issue as a time series of system states.

The problem that we address in this paper is of a different type. It is smaller yet (expected to be) more rapid. With the coming about of miniature and cheap GPS technology, we expect an upsurge in applications in which the whereabouts of objects is constantly monitored, and stored for future analysis. The applications are manifold: mobile phone monitoring, traffic jam analysis, route planning, service vehicle scheduling, animal migration analysis, and indeed natural hazard monitoring; all these applications have an inherent, high level of dynamics.

To support such applications, databases and GIS systems should provide functionality to store positional traces over time that represent the objects’ movements, and allow easy analysis on them. Related queries come in many flavours:

- Where was object X at time t?
- Which object moved at the highest speed?
- At what time were objects X and Y closest to each other?

- At what time occurred the highest density of objects in area A?

Research into system support for such queries has only just started, and our objectives in this paper are humble. Our fundamental goal is to answer the first question above, from a database/GIS perspective. What techniques are needed to determine where some object was at a given time instant? We believe that this is a fundamental question underlying many of the other example questions.

1.2 Database issues

Although quite some work has been done in the area of spatio-temporal databases, existing models are not suitable for moving object representation and a proposal for a 'moving object data model' is wanting. This was recognized by (3), who looked into the typing, algebraic and functional issues of such a model.

The crux of databases supporting moving object storage and querying will be in (a) support for storing massive amounts of moving objects, each of which may have long historic traces, and (b) support for query language primitives to analyse their behaviour.

As we can make no *a priori* assumptions on the nature of object movement, the only feasible representation is a—possibly long, but finite—chronological sequence of previous positions. Extra information, such as *momentaneous velocities* or even *momentaneous accelerations* may be available, and should then be used. This availability is less far-fetched than one may think, as state-of-the-art GPS technology can deliver such data. A full discussion, including issues of error and error propagation, is beyond the scope of this paper. In Section 2.2, we discuss four types of moving object representation on the basis of the above assumptions.

With finite representations of an inherently continuous phenomenon like object movement, a naturally appearing issue is that of positional interpolation. This is the subject of Section 3, where we discuss various scenarios. We observe already that countless interpolation techniques exist, depending on available information as well as on the nature of the objects being represented, and that suitability of the technique applied is an expert question rather than a layman's. For this reason, we believe the end-user of a query language should not have direct access to the choice of technique, and thus that the database system should support it transparently (2).

In addition, the database should also be able to operate on large volumes of objects, and thus, the interpolations applied should be relatively simple. In the end, we are interested in striking a proper balance between precision of positional interpolation for many objects and the time complexity of the computations involved. For simple queries, the data complexity appears to be linearly dependent on storage size, and it seems therefore less important to consider.

1.3 GIS issues

Under the assumption that much of our pure moving object manipulations (i.e., analysis) will be performed by the database system, three issues remain to be dealt with at the GIS side.

The first of these is also analytic in nature, and addresses questions of the type

- Did object X at any time traverse area A?
- In its movements, has object X shown any preference for traversing areas of a certain category?
- At what time did most objects traverse area A?
- Is it plausible that object A always moved along network N?

These question types are hybrid in nature, as they involve the database to produce an interpolated trajectory for the objects, but also the GIS to combine that information with its knowledge on stored areas and networks.

This actually brings us to the second issue at the GIS side: data transfer protocols. Clearly, the GIS must accommodate the acceptance of object trajectories from the database. Initial quick-and-dirty solutions may resort to using line features for this, but surely many examples exist in which these do not suffice. Therefore, a deeper understanding of the temporal dimension to trajectories must eventually be provided.

Finally, a third and exiting issue is the visualization of object movement in a GIS. Current GIS are too 'static' to accommodate this well, and new techniques must be found. It seems straightforward to think of artificial video construction to visualize these highly dynamic things, but the usefulness of these for 'visual exploration and analysis' seems to be at least doubtful. More static visualizations may allow closer scrutiny.

2 DATA REPRESENTATION

2.1 Moving objects

Objects whose position and/or extent changes over time are called moving objects (3, 1). Any change in position or extent will be viewed as movement. Simply speaking, movement is a mapping of time into space that determines position and extent of the object at different points in time.

On the basis of the three primitive spatial data types—namely point, line and region types–we may identify three moving object types: *moving point*, *moving line* and *moving region*. Oil spills causing water pollution, for instance, can be considered moving points or (better) moving areas.

In this study, for the sake of simplicity, we only look at moving point representations and the associated interpolation techniques.

2.2 Moving object representations

Depending on the information available, we can identify five schemes of moving (point) object representation. They go from simple (when little information is available) to more complex (when we know directional speed and acceleration). We also discuss a fifth approach that we consider because it seems to hold promise as a data compression technique. The five schemes are discussed below.

2.2.1 $\langle epoch, location \rangle$ **sequences** Perhaps the simplest moving object representation is a sequence of $\langle epoch, location \rangle$ pairs. To determine the (a) possible location of the object at some arbitrary time instant in this representation, interpolation or extrapolation must be used.

Such sequences of time and location are stored in the database, one sequence for each moving object that we want to represent. Elements of a sequence will have $\langle t_i, X_i, Y_i \rangle$ values, where t_i is the epoch and X_i and Y_i are location coordinates of the point i along the oil spill path.

This approach requires powerful data acquisition methods that operate at small time intervals, obviously because the location presumably changes frequently. As we noted above, the new small and handy GPS receivers provide the possibility to acquire these value sequences.

2.2.2 $\langle epoch, location, direction \rangle$ **sequences** Inclusion of more information in the scheme, will help to predict the possible past/future positions more accurately.

In this representation, a sequence of time, location and direction is stored in the database for each object. Thus, we have a sequence of $\langle t_i, X_i, Y_i, d_i \rangle$ values, where d_i is the direction of the oil spill movement at point i.

Having direction values is useful to obtain a better understanding about the object's trajectory. It can easily be seen that in the previous scheme, there is little information about the path and that many more different paths are likely between the two locations.

2.2.3 $\langle epoch, location, direction, velocity \rangle$ **sequences** Absolute values of velocity also help to determine the possible trajectories of oil spills more precisely. In the case where the possible location is an area instead of a point, involving velocity in the computation makes this area as narrow as possible.

A sequence of time, location, direction and velocity combinations is stored in the database for each moving object. So, we define sequences of $\langle t_i, (X_i, Y_i), d_i, v_i \rangle$ values, where v_i is the velocity of the oil spill at point i.

GPS receivers are capable of recording velocities at acceptably accurate levels.

2.2.4 $\langle epoch, location, direction, velocity, acceleration \rangle$ **sequences** Similar to velocity, to know the acceleration is useful in approximating the oil spill's trajectory more closely to reality and to obtain better estimates of the affected area. Observe that acceleration is a vector with a possibly different direction than that of the velocity.

The following spatio-temporal queries can be answered using the above schemes.

- Which area is affected during the $[t_1, t_2]$ interval?
- When is the oil spill in the specific location?
- Which are the oil spills that take place in a specific area at time t?

2.2.5 $\langle epoch, velocity, f(t)\rangle$ **sequences** A characteristic common to the above-mentioned methods is their use of location as an important value. But moving objects change their position frequently, which leads to high-volume streams of acquired data. There are alternatives that allow lower data volumes for moving object representation.

One of the alternative methods, the basis of which was introduced in (6, 7) and from which this paper tries to expand, is to use a distance function instead of explicit locations and consider an initial point as the start point of movement. In this case, during the movement, the spill's distance from the initial point will have changed.

As oil spills are physical objects with clear boundaries, Newtonian laws can be applied to them. An issue that should be paid attention to is that for the time being these representation methods are not very applicable. Especially this holds for oil spills monitoring because of difficulty in acquiring the data about velocity and acceleration. Perhaps, the data about velocity and acceleration of the water can provide an idea about the velocity and acceleration of oil spills, also.

Linear/Constant/zero acceleration and constant direction in each interval are assumptions that can be used in this type of representation. Constant speed, constant acceleration or linear acceleration will lead to differently defined schemes:

The first scheme assumes the use of velocity values and stores values after any change in velocity. It means we perform a step by step monitoring of velocity and that velocity is constant between two consecutive changes. Therefore, the acceleration in each interval is 0. The following formula provides the position at time t:

$$\overline{f(t)} = \overline{v}.t + \overline{p_0}, \tag{1}$$

where $\overline{v}$ is a constant velocity and $\overline{p_0}$ is the initial position.

The second schema assumes to use acceleration value instead of velocity. Apart from the difficulty to acquire this value, this representation generalizes the first one. Comparing two subsequent acceleration values will allow us to determine if acceleration is zero, which means constant velocity, or if it is constant or changes linearly. In the case of zero acceleration we have formula 1, while in the case of constant acceleration we obtain formula 2 to define the position at time t:

$$\overline{f(t)} = \frac{1}{2}.\overline{a}.t^2 + \overline{v_0}.t + \overline{p_0}, \tag{2}$$

where $\overline{a}$ is a constant acceleration, $\overline{v_0}$ is the initial velocity and $\overline{p_0}$ is the initial position.

For the case where acceleration changes linearly, we have formula 3 to obtain the position at time t:

$$\overline{f(t)} = \int\int \overline{a}.\partial t^2 + \overline{p_0}, \tag{3}$$

where $\overline{a}$ is momentaneous acceleration and $\overline{p_0}$ is initial position.

It is important to notice that these formulas should be applied in X and Y separately, which is why we have used vector notation as in $\overline{p}$.

The latter representation schemes may be useful in compressing the data sequence while on the other hand, as it makes the interpolation technique explicit, it mixes known values—velocities/accelerations at the epochs—with approximated values. The schemes are thus less orthogonal to choice of interpolation. Further work is needed to determine the computational complexity and efficiency of these approaches for implementations.

In the choice of representation scheme, several factors should be taken in account, some of which we list here:

- **Applicability**: $\langle epoch, location\rangle$ sequences forms the simplest method available, and is always applicable. The inclusion of more information such as direction, velocity or acceleration may present difficulties, but does allow to obtain better approximation results. In comparison, the representation scheme described in Section 2.2.5 does not seem as applicable.
- **Generality**: It is difficult to find a general function that faithfully represents an oil spill's movement in all cases. Clearly, any object may move by its own pattern and may even change patterns between time intervals. Section 2.2.5 represents object movement along a straight trajectory with constant/zero/linear acceleration, while other representations are more general as they do not impose an interpolation technique.
- **Data acquisition methods**: Usually, position is easier to acquire than direction, velocity and acceleration. But the added value of obtaining some of the latter should not be ignored, and may certainly help to obtain better approximations of the object's trajectory.

- **Interpolation technique**: When exact data is not available, we need to apply functions and provide them with 'circumstantial evidence'. In Section 2.2.5, the representation scheme assumes a continuous function, and application of the function is easy for the simpler cases. It remains to be seen whether other uses of the interpolation function—such as generation of the full trajectory for visualization or further analysis purposes—are equally straightforward. In the other schemes, there is no fixation of the interpolation/extrapolation method, and the choice can be based on application criteria.
- **Data and time complexity**: In the presence of large collections of moving objects, the computational complexity of interpolations and generation of the full trajectory should be taken in account. It is our purpose to strike a balance between optimal trajectory approximation, natural representation of the object kind, and efficiency of the data structure and its functions.

3 INTERPOLATION TECHNIQUES

Lacking any further information, and assuming the least possible further constraints, we must observe first and foremost that the actual trajectory followed by the object between two location measurements is unknown. Our work is based on the assumption that the interval between subsequent epochs is small enough to allow us the working assumption 'fitting least curved trajectory'. By 'fitting' we mean that all measurements obtained are free of error, and thus, amongst others, that locations are true locations. The issue of error we hope to address in a later study.

The above assumption, when applied to a scheme with epochs and locations but nothing else, trivially leads to a straight segment interpolation. Since there are no further constraints, the interpolation of the X coordinate can be obtained independently of the interpolation of the Y coordinate.

Surely, the choice of interpolation method should be based also on the nature of the moving object population, although at present we only have vague ideas of what this should amount to. Processing efficiency is a further consideration, as is the type of query that needs to be answered. A snapshot question—Where was the object at time t?—may allow a more advanced approach than historic questions—What was the full trajectory of the object?

There are two options to interpolate at time t: use data from the previous and the next epoch only, which means using only two points, and use data data from n previous and m following epochs, $n, m > 1$.

For each of the schemes discussed earlier, we look at some interpolation techniques. The simpler case is when we consider only the information from the epochs that determine the smallest time window around the time instant under discussion.

3.1 Using the two nearest epochs

Using the only the nearest epochs, one before and after the time instant of interpolation, leads to the following interpolation techniques. We assume polynomial interpolator functions.

3.1.1 $\langle epoch, location\rangle$ **sequences** The pairs $\langle t_i, (X_i, Y_i)\rangle$ and $\langle t_{i+1}, (X_{i+1}, Y_{i+1})\rangle$ allow to have four equations (two for each dimension at the two epochs). Therefore, interpolation curves are linear polynomial as presented in the Equations 4.

$$X(t) = a_0 + a_1 t \tag{4}$$
$$Y(t) = b_0 + b_1 t \tag{5}$$

Solving these equations and determining the involved parameters leads to simple position functions for any point in time. Clearly, by having only $\langle epoch, location\rangle$ information we can not infer the value of velocity, direction or acceleration.

3.1.2 $\langle epoch, location, direction\rangle$ **sequences** With two triplets of the form $\langle t_i, (X_i, Y_i), d_i\rangle$, four location equations and two direction equations (one each for an epoch), we may approximate with six parameters. This allows cubic parametric location curves as represented in Equations 6 and 7 and the direction can be defined using the first derivatives of X and Y as represented in Equation 8.

$$X(t) = a_0 + a_1 t + a_2 t^2 \tag{6}$$
$$Y(t) = b_0 + b_1 t + b_2 t^2 \tag{7}$$
$$d(t) = arctan\Big(\frac{\partial Y(t)/\partial t}{\partial X(t)/\partial t}\Big) \tag{8}$$

By solving for the parameters, the location, direction and the speed can be obtained at any point in time. It has to be noted that as the direction has been defined there is no need to have more points in the interpolation.

3.1.3 $\langle epoch, location, direction, velocity\rangle$ **sequences** We can also assume the presence of velocity information. With two quadruples of the form $\langle t_i, (X_i, Y_i), d_i, v_i\rangle$, we will have eight equations; X, Y, velocity and direction at each of the epochs. Therefore, the parametric curves are defined having eight parameters and are represented in Equations 9 and 10. The velocity is defined in Equation 11.

$$X(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{9}$$
$$Y(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 \tag{10}$$
$$s(t) = \sqrt{(\partial X(t)/\partial t)^2 + (\partial Y(t)/\partial t)^2} \tag{11}$$

By combining the Equations 8 and 11 into Equations 12 and 13, an easier system of equations can be used for solving for the eight parameters. Having the eight parameters identified, the location, direction, speed and acceleration are determined for any time instant.

$$x'(t) = v(t).cos(d(t)) \tag{12}$$
$$y'(t) = v(t).sin(d(t)) \tag{13}$$

3.1.4 $\langle epoch, location, direction, speed, acceleration\rangle$ **sequences** If even direction and magnitude of the acceleration is known, four more equations can be introduced leading to a number of twelve equations, which can be used for obtaining twelve parameters in the parametric curves of Equations 14 and 15.

$$X(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \tag{14}$$
$$Y(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5 \tag{15}$$

By solving these equations, the location, speed, direction, and acceleration can be obtained for any point in time. The equations of acceleration, direction and magnitude, can be written similarly to Equations 8 and 11 having the second derivatives $X''(t)$ and $Y''(t)$. Those two equations can be rewritten similarly to Equations 12 and 13 to have simpler equations for solving for the parameters.

It has to be noted that only two points with their available attributes are used in the above interpolation methods. This means that the interpolated curve connects each two consecutive points. This consideration is a good assumption if the direction of movement is known in the representation scheme. If the direction is not known, more epochs should be used for interpolating the same curve. One such technique is the use of spline curves, which we discuss below.

3.2 Using more than two epochs

In the case of $\langle epoch, location\rangle$ sequences, we may assume continuity and differentiability at the epochs between subsequent—connected, polynomial—curves of the trajectory. The technique of splines can then be used.

The assumption of continuity of the curves at the epochs forces the two curves to be equal at the epoch. The differentiability (smoothness) of the curves at the epochs forces the first derivatives of X and Y of both curves at the epoch to be equal also. A similar argument can be applied for the second derivatives so as not to allow abrupt change in acceleration.

The polynomial degree of the spline equations can be defined according to the number of parameters that are used. The first and last curve of the trajectory have a lower degree than the intermediate curves since there are no differentiability or acceleration constraints. Spline may provide more values for velocity, direction and acceleration even if they have not been defined.

4 CONCLUSIONS AND FUTURE WORK

We discuss in the paper a number of options for moving object representations, and the associated potential interpolation techniques. The rapid to-market development of cheap GPS technology brings about the question of how to handle this type of information in larger data volumes.

The paper presents a first attempt at a systematic study of this problem, but it is too early for firm conclusions. We must consider that information originated from GPS is not only positional, but also may involve notions of direction, velocity and acceleration. The proposed representations accommodate this type of extra information. It remains to be seen what is the added value of such information, but this requires a more empirical study in application domains that are likely still in their infancy.

Our approach assumes there is no error in the data obtained, and thus we did not consider least squares methods as an option. The assumption of adequate temporal resolution has made us pose the assumptions of continuity and differentiability.

Working with parametric curves gives a chance of representing general object movement such as rotations and periodic movements. Using interpolation of the data, the unmonitored positions as well of oil spills can be identified, which may help to target the search areas for overcoming pollution problems. We are currently also looking into extrapolation techniques.

Much work remains to be done. We are looking into theoretic and practical quantification of the space/time complexity of the techniques proposed. Our work reported on here only deals with snapshot questions, not with more general questions with a temporal dimension. Much depends on the general characterization of object trajectory that can be derived from a finite series of measurements. Even simple questions as how much distance did the object travel over some time interval defy a simple answer right now. The work reported here focuses on moving point objects, whereas moving lines and moving areas are certainly equally interesting—yet a bit more demanding computationally. We are working on schemes where our moving point work can be applied for lines and areas also.

There is a whole range of potential applications. We have highlighted the monitoring of oil spills in this paper a little bit, just as a non-trivial case in point. In the case that continuous remotely sensed images for the polluted area are available, parameters can be obtained and predictions can be tested against the images by degrading the image data.

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