LINEAR REFERENCING SYSTEMS AND THREE DIMENSIONAL GIS

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ABSTRACT

Many of the difficulties associated with geographic information systems (GIS) result from the use of linear referencing systems (LRS) and color coding as surrogates for true three-dimensional (3-D) data. LRS data cause particular problems when modeling 3-D transportation structures and properties such as true distance over hills, freeway overpasses and on-ramps, or commuter-rail lines sharing a right-of-way with a highway. As transportation models demand greater detail and complexity, the color coding required to properly represent them approaches intractability and clouds the dynamics of the model. The theoretical foundation presented here exploits the sub-meter accuracies offered by the Global Positioning System (GPS) for field positioning. The advantage of this theory is the ability to model transportation infrastructure without the need for storing data in complex LRS schemes via dynamic segmentation. Particular emphasis is placed on wide-area differential GPS (WADGPS), which offers sub-meter performance independent of local base stations. Initial findings indicate a transportation model based on 3-D data will be void of the pathological cases that have begun to plague LRS, dynamic segmentation, and coding. This proposed use of GPS-based data structures could have revolutionary influence over future GIS data designs, as well as how transportation data is collected, shared, and utilized.

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ACKNOWLEDGMENT AND DISCLAIMER

This work was supported by the United States Department of Energy and was performed at Sandia National Laboratories under Contract DE-AC04-94AL85000.

INTRODUCTION

The work presented herein explores a new direction in GIS for Transportation (GIS-T) infrastructure modeling which is potentially free of the pathologies associated with current LRS data models. A model is proposed which builds towards a fully structured 3-D GIS as supported by GPS and its World Geodetic Spheroid 1984 (WGS84). Also outlined are the mathematical strategies necessary to adopt legacy LRS models into this proposed spherical GIS-T architecture.

GIS-T is built up from three layers:

- A fundamental arc-node (point, line, polygon) layer as derived from traditional cartographic systems (vector or raster). This model is frequently linked to tabular details through a relational database manager.
- A 1-D offset measurement technique known as a linear reference system (LRS).
- Dynamic segmentation as an enabling tool for assigning multiple attribute sets over a single linear event.

Many of the current constraints found in GIS stem from decisions that made sense at the time they were made, but are no longer valid. The 2-D map was an acceptable representation when overpasses were rare and various modes of transportation were largely disjoint. During these earlier days, LRS was vital because few alternatives could record absolute field locations easily. A field accuracy of 0.5 km was acceptable because other than the distance measuring instrument (DMI) there was no alternative.

Dynamic segmentation was also the only alternative for representing more than one event along a linear feature. Because classical GIS-T techniques required the use of multiple local reference frames, data sharing between agencies was difficult or impossible. Problems multiplied as systems grew in complexity and temporary fixes were added to overcome the multiple datum requirement.

Multiple datum LRS and color coding of complex infrastructure objects often result in misleading or incorrect computation, identified by Sutton (1996) as network pathologies. The incorrigible nature of these pathologies suggests the need for a radical change, rather than evolutionary changes to either traditional LRS data models or national datums (see Fletcher 1996, Vonderohe, 1995, 1996, Dueker and Butler, 1996).

The fundamental thesis of this paper is that these convoluted historical constraints are no longer valid. There are clear indications that the layered LRS/multiple datum architecture is incapable of representing contemporary transportation features. Because GPS service is now ubiquitous, it is now possible to build a fully three-dimensional and topologically correct model for transportation infrastructure.

The GPS provides the common origin needed to make data interchange fast, easy, and error-free, just as a geometrically correct 3-D GIS-T model would eliminate the pathological errors bound within the limits of LRS. Mutually incompatible datums and complex dynamic segmentation coding techniques would be replaced by a common language, and the gap between precision drafting methodologies and connectivity-bound topologies like GIS could be closed forever. The potential of 3-D GIS-T data storage should be viewed as profound and ready to meet the needs of local, state and federal agencies forced to accomplish more with less.

HISTORICAL PERSPECTIVE

The literature is continues to indicate the arc/node/polygon vector data model has not significantly changed over the past thirty years (Vander Veer and Bespalko, 1997) and may no longer be meeting the needs of GIS-T applications (Burkholder, 1993, Fletcher, 1995, 1996). For example, there are a variety of problems associated with traditional data models employing local datums:

- A fundamental incompatibility between arc precision and arc connectivity.
- An inability to share data because of incompatible datums or multiple reference frames.
- Network pathologies stemming from 3-D transportation modeling needs.
- Data structures designed for cartographic visualization rather than rigorous mathematical modeling.

- Complex layers of quick fixes to accommodate 3-D objects in 2-D data structures.

GIS grew from cartographic science, just as CAD grew from drafting. Initially, CAD was also a 2-D system, and if a view from another angle was required, the entire drawing had to be rebuilt. The system was improved by redefining CAD tools to build a 3-D digital model of the object which can be rendered as a drawing from any specified angle. The transition from 2-D to 3-D is much harder for GIS and GIS-T than CAD systems because CAD systems do not require the all-encompassing frame of reference. The technology necessary to model an entire planet is complex, and this accounts for the divergence between CAD and GIS data structures.

Another, perhaps more pertinent, example is the evolution of computer graphics. The object in Figure 1a is drawn with no 3-D structure, much like present-day GIS. Color is added to the view in Figure 1b. The object is still 2-D, because the coding only adds visual (cartographic) license to an explicitly 2-D model. Figure 1c shows the illusion of a 3-D object is fully pursued in the 2-D environment. The colors, or coding, become extremely complex in order to shade the object properly, and additional lines are added to give an illusion of depth. The illusion is fairly compelling, but if a view from another direction is needed, the process must be repeated.

A new approach was required to transcend these limitations, and the graphics/CAD industry began experimenting with 3-D models without the additional layers of color coding or artificial lines needed in 2-D systems. It was recognized the 3-D data model was the only approach that could support rendering from any angle, as well as the volumetric and other analysis functions demanded by modern design processes. The new data model offered height, width, and depth, not fancy colors and lines to represent depth. It was no longer a problem to measure the true distance across a sloping surface, model 3-D networks, or assign multiple data sets to single features through absolute coordinates.

As a result of the investment in 3-D CAD and graphics technology, there are now decades of experience and information which can be utilized. One of the key changes precipitated by the switch to three dimensional technology was the separation of model building (see Figure 2a) from visualization. Once the model was built, it could be visualized from any point-of-view. (See Figures 2b and 2c).

Low cost digital technologies such as GPS, along with the new object-oriented data management systems, now provides the tools to unify datums and ground monuments into a single coordinate system and origin: the WGS84. Just like the graphic/CAD industry, the GIS pathologies associated with 2-D data models evaporate as 3-D constructs are forged over a single absolute origin. Thus the development issues related to switching to 3-D are technical, not theoretical. Issues remain regarding how much data the objects will require for storage, not whether the 3-D model will arrive at the correct answer. Most importantly however, attacking the risks presented by the technical issues is warranted since the ramifications are far-reaching. All the necessary technologies are available for a revolutionary new spatial data technology but much research must be done to exploit the strengths of each component.

NETWORK PATHOLOGIES

Two-dimensional GIS has been built from three fundamental topologies: connectivity, contiguity, and area definition. Within intended limits, 2-D computations typically offer elegant solutions for spatial algorithms. However, as priorities shift from cartographic representation towards dynamic modeling, the classical arc-node topologies break down in three domains:

- The true distance measurement across sloping or hilly terrain.
- The representation of 3-D structures such as overpasses and on-ramps.
- The assigning of multiple routes over a single arc.

Rather than adopt a 3-D CAD data model, the GIS community opted for additional layers of topological ruling, primarily route systems, and LRS. Unfortunately, these deepening layers of abstraction each spawn a different set of pitfalls. Pathologies, such as those described by Sutton (1995, 1996), result when feature intricacy exceeds the modeling capabilities of the available topology. As each new fix is added to compensate for a deficiency, new and enigmatic pathologies manifest themselves.

For example, dynamic segmentation is considered the fourth level of traditional 2-D GIS topology. Point event (traffic accidents), discrete linear features (a pavement study area), and continuous linear events (pavement type), may be mapped to an arc-node assembly or route. Nevertheless, many pathologies are precipitated:

- Discontinuous routes: Routes may stop and start for various reasons.
- Dog leg routes that share common sections of other numbered highways.
- Split roads which may be of unequal lengths.

- Cul-de-sacs that lack a conventional reference method because the available topology cannot define it without additional logic.
- Transition ramps between two different numbered routes.

The emerging demands of Intelligent Transportation Systems (ITS) networks further exceed topological limits through the need for:

- Routing by lane
- High Occupancy Vehicle (HOV) lane representation
- HOV lanes that by-pass toll plazas

By definition, LRS is a relative location system; points are referenced to a central datum or origin. Typically, multiple LRS systems imply varying data quality at different scales. In other words, accuracies sufficient at small scales may not be accurate at larger scales. A fundamental hypothesis resulting from this observation is that multiple datums will always be mutually incompatible as long as the datums are defined in terms of different scales. For example:

- Datum locations themselves change as map scales change.
- Without common datums, entire libraries of LRS data cannot be shared.
- Automatic data conflation between map scales cannot be accomplished because feature locations appear to move in absolute space.
- Without absolute coordinates, features lose definition as scales decrease.

Tracking absolute coordinates is the only solution to the scaling problem, and absolute coordinates are now readily available via GPS and WADGPS.

The principle purpose of GIS-T is to model transportation systems. Previous models have focused on single time periods such as peak commute. Simulation models aim to mimic traffic movements at microscopic scales (i.e., turning movements at junctions in units of seconds or minutes). These micro-effects are necessary to elucidate the tangible details of complex networks; however, traditional arc-node, route system, and LRS topologies cannot segment the 3-D world into the essential tractable model segments:

- Fictitious links must be coded to represent turning movements.
- Complex clover-leaf and on-ramp scenarios cannot be accommodated.

- Traffic assignment nodes sometimes do not fall on real nodes. Changing the assignment location to meet the limits of the arc-node model changes the result of the traffic routing model.
- Corridor links representing multiple streets cannot be represented.

In an attempt to maximize model validity, numerous levels of assumptions and dimensional work-arounds must be formulated and implemented. A calibrated model cannot be universally applied to new data because the calibration depends on the datum. The adoption of a single global datum would unify all global measures to a single absolute point.

GPS AND THE WGS84

GPS is representative of many new technologies which could facilitate the uprooting of 2-D and 1-D coordinate strategies. However, the transportation modeling community has voiced several concerns associated with GPS and its use in transportation:

- Availability.
- Selective Availability (SA) to degrade GPS accuracy to 100 meters.
- The need for fixed base stations.
- Multipath problems associated with urban and mountainous terrain.
- An inability to easily incorporate GPS data into legacy linear referencing systems.

GPS availability was problematic during the 15 years of testing and deployment, which is why GPS surveying is the application with the widest deployment. Crews were able to avoid surveying during periods when GPS measurements were inaccurate. This occurred when an inadequate number of were above the horizon. This changed on 8 December 1993, when the last GPS satellite was deployed. Now coverage with at least eight satellites above a 15 degree mask angle is assured.

With the least expensive GPS equipment, intentional corruption of the GPS signal and other error sources degrade positioning service to no better than 100 meters. Even then, local area differential service (LADGPS) can provide sub-decameter performance within the range of a qualified base station.

The Wide-Area Differential GPS (WADGPS) network, as first proposed by Brown (1989), removes the need for local base stations. Correction information from a nationwide network of integrity monitors is combined with improved ephemeris (satellite position) data and atmospheric models to build pseudorange corrections for individual service sectors across the globe. Sub-meter accuracy is easily achieved independent of base station locations. WADGPS methodologies and deployment have caused major policy problems within the GPS decision authority and have prompted the recent Presidential directive to deactivate Selective Availability. However, the directive will not be implemented until an effective WADGPS jamming capability has been achieved (RAND 1996). Multipath problems in urban and mountainous regions remain a problem; however, improved antenna design, processing algorithms, and Russian GLONASS signals are helping to blunt some of the difficulty. Nevertheless, with careful field planning and data collection implementation, adequate GPS coverage should be available in most areas.

The final difficulty, adapting GPS information to legacy systems, was addressed by Bespalko and Sutton (1996). GPS is a three dimensional technology (Kaplan, 1996) that uses a standard Cartesian coordinate system:

$$\underline{x}_i == \{x_i, y_i, z_i\}$$

The origin of the GPS coordinate system is the center of the earth, thus the coordinate system is referred to as Earth-Fixed-Earth-Centered (EFEC). For the sake of brevity, this discussion concerns the curve for a single segment of pavement. The curve is represented by a set of GPS points:

$$X == \{\underline{x}_0 .. \underline{x}_n\}$$

as shown in Figure 3a. The name Global Reference System (GRS) is proposed for the following formulation. Given the importance of relating distance and location, the organization of the spatial data will be to store the data as a function of distance, s:

$$\underline{x}(s_i) == \{x_i, y_i, z_i\}$$

This basic relationship allows the transformation between systems storing linear data and the proposed 3-dimensional GIS-T. The relationships transforming the data can be expressed in terms of basic multivariable calculus, where the transformation from a distance along the curve $\underline{x}(s_i)$ to the coordinate corresponding to the distance s is accomplished with the standard vector formula:

$$\text{A=Arc Length} = \int_0^s |\underline{x}'(t)|dt$$

Thus the solution to the problem *given s find* $\underline{x}$, which is found solving for the zero of the equation:

$$\text{f(s)} = \text{A} - \int_0^s |\underline{x}'(t)|dt \qquad (1)$$

where A is the desired length. Solving the equation requires numeric computation, which, in this case is, best handled with a non-linear approximation method known as the Secant Method:

$$s^{(n+1)} = s^{(n)} + h^{(n)} \text{ where } h^{(n)} = -f(s^{(n)})\frac{s^{(n)} - s^{(n-1)}}{f(s^{(n)}) - f(s^{(n-1)})}$$

In most cases, this approximation (which is a refinement of the well-known Newton's Method for finding the roots of equations) should converge on the solution in a small number of iterations. When spatial data is organized on a fixed distance, it may be possible to find the solution with no iterations because the algorithm is fully deterministic.

Similarly, the transformation required for the problem *given* $\underline{x}$ *find s*, involves solving for the root of the differential equation:

$$\frac{d}{ds}\left|(x^*, y^*, z^*) - (x(s), y(s), z(s))\right|^2 = 0 \qquad (2)$$

As in the case of determining the location corresponding to a distance down the road, the solution involves an application of the Secant Method.

Storing the spatial data as a function of distance allows for transformation between a distance (or arc length) system and a three dimensional Cartesian (or location) system and provides seamless forward and backward compatibility between future and legacy systems. This data architecture is the basis for a completely general method for exchanging data between arbitrary LRS systems. Thus, the GRS is also the ideal method for providing optimal data-exchange between existing LRS systems and is much simpler than calibrating a DMI.

Figure 3b schematically shows how the GRS and the mathematical formulation outlined above can be used to supply forward and backward compatibility as data is gathered in GPS format. To accomplish the exchange, the control points in the LRS must be marked using GPS coordinates and added to the GRS representation of the relevant transportation network. Once this data is provided, the GRS will have:

- the locations of the beginnings of each arc (or the set of x_0) for all of the arcs.
- the offsets or the length s for each linear datum.

Thus, Equation (1) above can be used to translate LRS data into the GRS. Similarly, once the control points used for the legacy LRS are added to the GRS, GRS data can easily be transferred back to the LRS via Equation (2).

Figure 3c demonstrates how the GRS can be utilized as the mechanism for exchanging data between two different LRS. It is important to note that the process of marking the control points with GPS coordinates is a fairly inexpensive operation and need only be done once. Once this is done, it is possible to transfer data between any other LRS that have also added GPS control points to the GRS. Switching to a GPS-based LRS should be a good long-term investment because the GPS data will be a valuable asset.

LIVING WITH LEGACIES

Two legacy issues must be addressed. The first legacy problem stems from existing databases. Three-dimensional data has been recorded as 2-D abstractions, and a great deal of these data now reside in 1-D linear reference form. The second legacy issue is that mapping and earth science have resided for the better part of two millennia in the 2-D world of projections, generalization, and various geoids. Scaling conventions have further expanded the paradigmatic gap between connectivity and precision. Taken as a whole, current practice cannot accommodate:

- the accuracy of new technologies.
- the need for information interchange.
- the modeling complexities of ITS.

This brings to light the economic balance of short term costs over long-term benefit. As demonstrated above, moving between legacy systems and 3-D solid coordinates is not difficult.

When combined with WADGPS positioning systems, legacy data accommodation is neither costly nor difficult. The main impediment to acceptance of a GPS-based GIS is a unified 3-D data structure specification and a covenant to demand software vendor support.

CONCLUSIONS: REQUIREMENTS FOR THE NEXT GENERATION

New information techniques, including GIS, GPS, and rapid data exchange via the internet, are presenting options for data exchange. The legacy practices of multiple datums, projections, and local reference frames cannot accommodate the accuracy and capabilities of these new technologies; and the ability to exchange information has created its own demand for compatibility. For example, counties have traditionally passed information to the state DOT, who, in turn, filed their Federal reports. Reverse information flow was never designed into the system because reference frames were not compatible. A common datum presents new options, and is forcing a revolution from the bottom up.

The transportation community must ask itself three questions:

- Is the transportation community willing to discard attempts to establish a national LRS datum?
- Who are the 3-D GIS data model stakeholders and would the software vendors entertain research into single coordinate system, solid geometry data model?
- Should initial tests of the equations derived here be conducted with a representative legacy system?

GIS-T, and GIS in general, are at the same crossroads that CAD reached twenty years ago, and, computer graphics reached recently. The limits of the current GIS technology are reaching a point where the most logical alternative is a radical change in direction. Unfortunately, the GIS community must also consider the ramifications of dropping two thousand years of cartographic legacy, and, adopting a fundamental change to survey and land management in general. The technology is in place for a major break-through in GIS; the issues with adopting the new technology are technical, not theoretical. On the other hand, the problems within LRS and multiple datums are indeed theoretical ones, and those problems are unlikely to ever be solved.

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