Error-sensitive GIS development: technology and research themes

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Abstract

The current lack of error-sensitive functionality found in commercial GIS is at odds with the research focus error-sensitive GIS development has enjoyed over recent years. In an attempt to address this undesirable situation, this paper reviews a number of key error-sensitive GIS research themes, based on experience gained during a three year research project into error-sensitive GIS development. The approach taken here contrasts with many other papers in the literature, since the issues raised are biased toward the error-sensitive GIS user's rather than developer's perspective. The paper concludes that from the user's perspective it is possible to identify a number of simple reformulations of current research that would help bring about the desired increase in availability and use of error-sensitive functionality within commercial GIS technology and applications.

1. Introduction

The endemic nature of error in GI is widely recognised, leading to the description of error as a "function of information" (*Goodchild, 1995*) and a "fundamental dimension of data" (*Chrisman, 1991*). Correspondingly, the development of what have been termed *error-sensitive GIS* (*Unwin, 1995*) has been long accorded a high priority in GIS research (see *Goodchild and Gopal, 1989*). Despite more than a decade of research related to spatial data quality, the translation of this research into viable technology has not been straightforward. While considerable effort has been expended on developing spatial data quality standards and computational models of spatial data quality, there is little evidence of such work filtering through to commercial GIS applications or technology.

This paper relates experiences and conclusions drawn from a three year PhD research project into the development of error-sensitive GIS. The error-sensitive GIS development process can be though of as comprising three distinct stages: first, deciding upon the core data quality concepts; second developing and implementing an error-sensitive data model based on these concepts; third, developing interfaces for the error-sensitive GIS to deliver the error-sensitive services and functionality to users. However, by focusing on the development process, the role of the user in error-sensitive GIS research is often marginalised or neglected: users' requirements are an explicit component of the third and final development stage alone. This paper argues that the primary goal of any error-sensitive GIS is to facilitate the application and understanding of uncertain GI by users. As a consequence, the three development stages are more appropriately viewed from a user-biased perspective. Three user-biased themes are identified and investigated in this paper, and can be thought of as a mirror-image of the development process outlined above: error-sensitive GIS use; error-sensitive data models; concepts of data quality. The relationship between user- and developer-biased perspectives is represented in Figure 1, where increasing depth implies increasing levels of abstraction from the user's point of view. The following discussion explores each of these three themes in turn and attempts highlight resonance and dissonance between the user-biased and developer-biased perspectives. While considerable further work remains, the outlook is relatively positive. The paper concludes that the goal of off-the-shelf error-sensitive GIS suitable for general use is certainly realisable, potentially in the not-too-distant future.

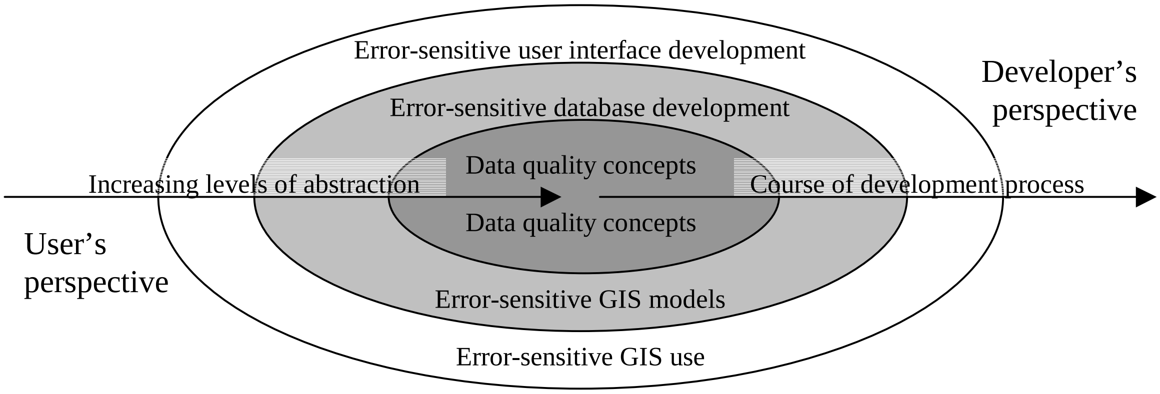


Figure 1, Different perspectives on error-sensitive GIS

2. Error-sensitive GIS use

An obvious criticism levelled at many spatial data quality standards and research articles is the emphasis placed on the storage management and propagation of information on spatial data quality, but not on how use such information. As suggested above, the conflict between the developer's and user's perspectives may in part be to blame for this imbalance. One area where developer's and user's perspective may be in harmony is in the need to address the *fitness for use* of uncertain GI.

2.1 Fitness for use

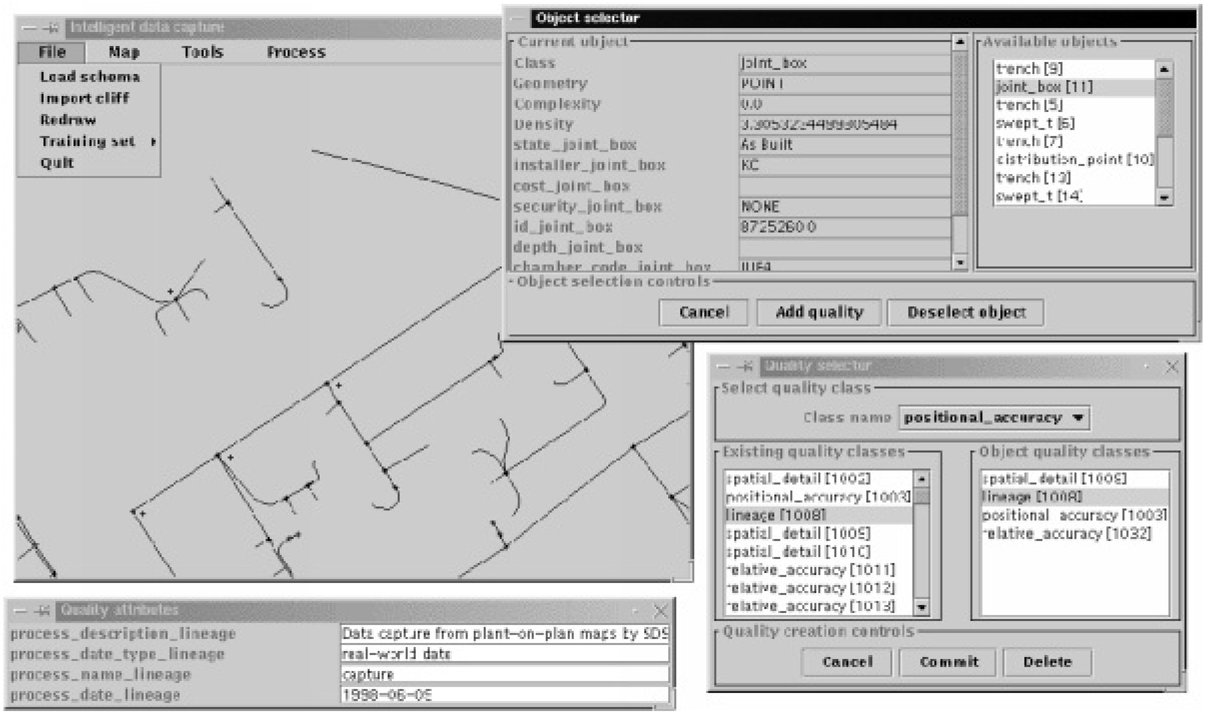
The assessment of fitness for use requires that data producers supply enough information about the quality of a data set to enable a data user to come to a reasoned decision about the data's applicability to a particular situation (*Chrisman, 1991*). Fitness for use apportions and emphasises the responsibilities between data provider and data user. The data provider has a responsibility to provide explicit, appropriate information on uncertainty along with data. The data user has a responsibility to ensure the data is on applied to problems where such a use is apposite. Both the question of what constitutes 'appropriate' information provision and the question of whether a particular use is 'apposite' necessarily involve an element of subjectivity. However, it is unrealistic to expect, as some authors have suggested (eg *Agumya and Hunter, 1997*), that the fitness of a data can every be assessed entirely objectively. Rather than a simple 'yes' or 'no' answer, 'fit' or 'unfit', the question of fitness for use will almost always yield an answer qualified by a degree of subjectivity.

Fitness for use has been successful because it comprehends the diverse nature of GIS. The various "information communities" that use GIS (*Open GIS Consortium, 2000*) have traditionally adopted different approaches to the management of error in information. Photogrammetrists, geodesists and surveyors have highly developed techniques for increasing precision and minimising error (*Mikhail, 1978*) and for mathematically modelling error (*Chrisman, 1982*). Cartographers aim to control, represent and communicate levels of uncertainty (*Chrisman, 1991*). Computer science emphasises the enforcement of consistency within an information system (*Hunter, 1996*). Fitness for use accommodates all of these different approaches, providing a basis for error-sensitive GIS which does not prejudice one approach over another.

2.2 Error-aware GIS

From the discussion above, it is to be expected that different information communities who use GI may have highly heterogeneous approaches to uncertainty in GI. Fitness for use is a useful paradigm for error-sensitive GIS because it provides a common baseline for uncertain GI management across these heterogeneous communities. Two requirements for error-sensitive GIS user interfaces follow. First, the heterogeneous approaches to spatial data quality adopted by different information communities may demand that the range of error-sensitive GIS interfaces be similarly heterogeneous. The need for heterogeneous user interfaces can be tackled by adopting an open GIS architecture. An open GIS architecture can allow rapidly developed user interface clients to achieve very high levels of integration with core error-sensitive GIS database servers, at the same time as preserving a clear separation between user interface and database. Second, the need to support the context dependent, partially subjective reasoning processes used in the assessment of fitness for use can be tackled through the use of artificial intelligence (AI) techniques. AI techniques allow domain specific user interfaces to target particular information communities' needs.

For example, the interface shown in Figure 2 was developed to address the data quality requirements of a telecommunications company (Kingston Communications, UK) during data capture. There exists a relatively high level of awareness of quality issues within the utilities industry, especially with respect to the development of integrated multi-utility LIS. However, very often such quality information is simply not collected by utility companies and so the process of assessment of fitness for use quickly stalls. The tool in Figure 2 uses an *inductive learning algorithm* to derive rules that describe the quality of a data set based on a small pilot quality assessment. Using these automatically learnt rules, the quality for an entire data set can be deduced from a relatively small quality assessment, given certain assumptions elaborated upon in *Duckham and McCreadie* (*1999*). The interface shown in Figure 2 uses an open Java-based architecture to enable the user interface to achieve powerful yet flexible access to the underlying error-sensitive spatial data and functionality. The term *error-aware GIS* is used to refer to the extension of an error-sensitive GIS using open, intelligent user interfaces (see *Duckham and McCreadie, 1999*).



Class	joint_box
Geometry	POINT
Complexity	0.0
Density	3.3053224499905484
state_joint_box	As Built
installer_joint_box	KC
cost_joint_box	
security_joint_box	NONE
id_joint_box	87252600
depth_joint_box	
chamber_code_joint_box	UE4

Class name positional_accuracy

process_description_lineage	Data capture from plant-on-plan maps by SDS
process_date_type_lineage	real-world date
process_name_lineage	capture
process_date_lineage	1998-06-05

Figure 2, Error-aware inductive quality capture tool

Potentially, the concept of an *error-aware GIS* is able to fulfil the key requirement of users of uncertain GI: the assessment of fitness for use. So far, however, very little has been said about the characteristics of the error-sensitive data models and databases needed to support such interfaces. The next section explores the demands an error-aware GIS places upon the error-sensitive data model from the user-biased perspective.

3. Error sensitive data models

While a user's interaction with the data model employed by an error-sensitive GIS should be limited, the previous section highlighted that, even from a user-biased perspective, a consideration of the error-sensitive data model is still important. The error-sensitive GIS developed during this research was designed using object oriented (OO) analysis and design techniques, and implemented in Laser-Scan Gothic OO GIS. The section looks at some of the different design and implementation decisions surrounding error-sensitive GIS development and the importance of OO to error-sensitive GIS.

3.1 Integrating data quality and GI

The laudable desire to maximise reuse of existing software during the development of error-sensitive GIS has often led to a dichotomous approach to data quality, where information about spatial data quality is stored and processed in a separate quality sub-system (see for example *Lanter and Veregin, 1992*; *Ramlal and Drummond, 1992*; *Wesseling and Heuvelink 1993*). While this approach may take advantage of a user's pre-existing familiarity with a GIS, it also has two important drawbacks. First it introduces additional conceptual and computational complexity. As already noted, error is an endemic, inseparable component of GI. Choosing a data model that artificially separates quality and spatial data entails additional conceptual and implementational structures to maintain the connections between spatial data and its quality. Second, separate quality sub-systems tend to lead to global or generalised quality information applied to blocks of GI, for example on a per-layer basis (*Lanter and Veregin, 1992*). The inadequacies of such global, generalised data quality information are well documented, for example with reference to DEMs (*Fisher, 1998*). These two drawbacks of increased complexity and decreased specificity make it less likely that the dichotomous approach to spatial data quality will be able to meet the user's requirements for an error-aware GIS outlined above. Happily, this research indicated that it is possible to achieve the same high levels of software reuse through OO, without the need for a separate quality sub-system and its associated disadvantages.

3.2 Object-orientation and error-sensitive GIS

The central advantage of using OO in GIS is the superior semantic modelling capabilities when compared to other approaches, such as relational data models. Similarly with error-sensitive GIS, the complex, heterogeneous nature of uncertainty in GI can be more effectively modelled using OO than other techniques. From the user's perspective, OO systems should be able to decrease system complexity and better reflect users' intuitive expectations of spatial data quality as an integral part of spatial data at every level of the database. The system developed during this research used OO to enable spatial objects to manage their own quality. Individual objects, from large aggregated geographic features down to primitive objects, like 'coordinate' or 'pixel', can be interrogated regarding their own data quality. By taking advantage of inheritance strategies available in all OO systems, pre-existing OO data models can be transformed with the addition of a handful of classes at strategic points in the inheritance hierarchy. Adding error-sensitive classes at or near the top of an existing OO inheritance hierarchy effectively transmits error-sensitive functionality to all objects in the database. Further efficiency gains can be accrued by taking advantage of aggregation and association relationships between objects in the database. Rather than store quality information for every object in the database, individual objects can infer quality where appropriate from their associated or aggregate objects. The results of implementing such mechanisms proved both conceptually and computationally efficient (see *Duckham, 1999*).

3.3 Extending the OO model

A number of authors have noted the importance of retaining original observations when attempting to use and propagate error through subsequent operations upon the data (*Fisher, 1998*; *Heuvelink, 1998*). Some authors have propounded the concept of a measurement-based GIS (M-BGIS), where original survey measurements are retained to allow subsequent adjustment of the surveyed features in the light of resurveys (*Campbell et al., 1994*; *Goodchild, 1999*). Such M-BGIS can be seen as a logical progression from OO error-sensitive GIS. Where the error-sensitive GIS developed during this research was able to infer quality via association or aggregation relationships with other geographic objects, a M-BGIS should be able to deduce data quality from relationships to the underlying survey measurements upon which the object is based. Work by the author, currently under review, addresses this possibility. In the same vein, the use of encapsulated error models (*Goodchild et al., 1999*), where specialised error propagation processes are encapsulated alongside geographic objects, is also congruent with the OO approach advocated here.

4. Concepts of data quality

The discussion above highlighted the importance of an integrated approach to spatial data quality in error-sensitive GIS, and championed the use of OO as an efficient route to achieve this integration. All that remains is to define the underlying concepts of spatial data quality needed to represent and report uncertainty in the data model. While potential users of error-sensitive GIS may consider such concepts as of marginal interest, these core concepts are important to consider as they shape both the error-sensitive data models and error-aware user interfaces. Traditionally, spatial data quality standards have formed the basis of most approaches to spatial data quality (eg *Guptill, 1989*; *Ramlal and Drummond, 1992*, *van der Wel et al., 1994*). This research, however, rejected the used of data quality standards as a basis for error-sensitive GIS development. Instead a more flexible approach not tied to any particular standard was favoured. The remainder of this section critically evaluates a number of related conceptualisations of spatial data quality.

4.1 Data quality standards

For many years now, research into spatial data quality has been held in thrall by spatial data quality standards. The domination of the ‘famous five’ elements of spatial data quality (lineage, completeness, consistency, positional and attribute accuracy; *NCDCDS, 1988*) over research into spatial data quality exemplifies this phenomenon. However, the close relationship between standards and research into spatial data quality has not necessarily been a healthy one. Research in GI has thrived on the heterogeneity of concepts evident across the discipline. Arguably, research into spatial data quality has been hindered by an unquestioning acceptance of previous standards-based work. The author has argued in related work (*Duckham and Drummond, 1999*) that many standards can claim to be neither exhaustive nor exclusive and often have no clear theoretical nor empirical basis. In the absence of such a basis, it is unreasonable to expect standards to be flexible enough to deal with the highly heterogeneous requirement of different users anticipated in Section 2.2. The assertion that it is "widely accepted that data quality is described by five elements" (*Agumya and Hunter, 1997*) should be viewed critically.

Data quality standards are undoubtedly an important area of endeavour that can help to promote and disseminate a snapshot of current best practice in the fast moving profession of GIS. However, at the same time as being compatible with standards-based work, an error-sensitive GIS should admit a more heterogeneous conceptual approach to spatial data quality than is evident in most standards. Arguably, more flexible approaches do exist, discussed below.

4.2 Varied concepts of spatial data quality

Conventionally, geographic information is thought of as the product of a process of abstraction and representation of reality (*Maguire and Dangermond, 1991*; *Veregin, 1999*; *Worboys, 1992*). This essentially realist epistemology works well when discussing geographic information, but needs extending when dealing with spatial data quality. Crucially, in contrast to GI there is no meaningful concept of data quality in the 'real world'; it is only as a by-product of the deficiencies of abstracting and representing reality that data quality arises as an issue at all (*David et al., 1996*). Conceptual approaches, such as that identified by *David et al.* (*1996*) have the advantage of a clear theoretical basis, greater flexibility and wider applicability to diverse heterogeneous concepts of data quality than can be offered by data quality standards. In fact, the influential research of *David et al. (1996)* was conducted as part of the European Committee on Standardisation (CEN) work on a standard for geographic information (*CEN/TC287, 1996*). However, experiences with the error-sensitive GIS implementation outlined above, which was based on this approach, suggest that considerable further specialisations needed for the CEN standards are not necessary for error-sensitive GIS. The resulting implementation was able to support a much wider range of different data quality standards and systems than available within the CEN standard.

However, just as there is no one standard that can hope to address every users' needs it is not the intention to suggest that any one conceptual approach can necessarily satisfy the needs of every user of uncertain GI. A clear lesson is that considerably wider exploration of different concepts of data quality than has previously been evident in the research could be very beneficial. Different conceptual models are certainly possible. *Veregin* (*1999*) indicates some of the areas in which spatial data quality may help to address some of the critiques of GIS as a positivist, reductionist and instrumentalist discipline. Work currently in preparation involving the author is looking in more detail at ways in which critical human geography may be able to help develop error-sensitive GIS that can address the needs of users whose perspectives would otherwise tend to be marginalised by GIS.

Formal approaches are perhaps a surprising inclusion in a user-biased perspective on data quality conceptualisations, since most potential error-sensitive GIS users would not wish to be confronted with such formalisations. Yet formal approaches to *imperfection* in GI (*Worboys, 1998a*) reflect a growing move to widen the debate about different conceptual models of spatial data quality. Research by *Clementini and Di Felice, 1996* and by *Cohn and Gotts, 1996* offer related formal approaches to reasoning about spatial regions under indeterminacy. *Worboys* (*1998b*) develops a formal approach to imprecision in GI. Ongoing joint work involving the author is looking at the application of formal models of imperfection to practical spatial decision support mechanisms. While the use of formal approaches to spatial data quality can neither provide certainty nor guarantee correctness, formality is a powerful tool that can induce widespread agreement and help expand the currently limited conceptual basis for error-sensitive GIS.

5. Conclusions

The most encouraging conclusion drawn from this work is that the error-sensitive GIS functionality needed to address the highly heterogeneous and specialised requirements of potential error-sensitive GIS users can be developed within the framework of existing GIS technology. Arguably, a number of factors are still presenting a barrier to error-sensitive GIS technology making the transition from research project to commercial functionality. The failure to give enough weight to the *use* rather than the *development* of error-sensitive GIS technology seems to be a hindrance to the application of error-sensitive research ideas. The development of integrated approach to spatial data quality, for example based on OO ideas and technology, would further assist the uptake of error-sensitive functionality. Finally a widening of the debate surrounding the different conceptualisations of data quality should filter through to produce error-sensitive GIS that are better equipped to meet the requirements of the heterogeneous information communities that use GIS.

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