Generalisation of point data for mobile devices: A problem-oriented approach

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1 Introduction

Comprehensive literature reviews and empirical surveys conducted within large research projects (AGENT 1998, Stoter et al. 2009) suggest that research in map generalisation has mainly focused on line generalisation. The generalisation of point features and point sets has received only limited attention, with the exception of the generalisation of building groups, which for some contextual generalisation operations (selection, typification) and for medium to small scales can be approximated as point sets rather than small area objects. In recent years, however, point data have gained in importance due to new cartographic challenges, such as the advent of point-of-interest (POI) data in web and mobile cartography applications, as well as the predominance of point geometries in geographically relevant Web 2.0 applications.

Closer inspection of existing algorithms for point generalisation suggests that many of them have been conceived with a rather opportunistic perspective, concentrating on relatively ‘small’ problems. What is missing is a comprehensive, *problem-oriented approach* that uses a common conceptual grounding. Such conceptual frameworks exist for line generalisation, where they have had a very positive effect on the further evolution of research. For instance, the works by McMaster (1987a,b) on the evaluation of the properties of different line generalisation algorithms have helped better choosing appropriate algorithms. The methodology by Plazanet (1995, 1996) inspired the better characterisation of cartographic lines and the subsequent development of new algorithms (e.g. Lecordix et al. 1997).

With a focus on information portrayal on mobile devices this paper aims to contribute towards developing a problem-oriented approach for point generalisation. Starting off from an analysis of the factors defining the point generalisation problem (§2), existing algorithms are then categorised and reviewed, retaining those algorithms with a potential for mobile mapping (§3). The results of these two sections then feed into the proposal of a workflow for point generalisation in the mobile context (§4). As the work reported is still ongoing, the proposed workflow is still preliminary, we will give an outlook on experiments that are planned to empirically assess the feasibility of the proposed workflow (§5).

2 Defining the point generalisation problem

Since our task is to develop a problem-oriented workflow to point generalisation, we must start by defining the problem. We will do this by deconstructing the problem into its defining factors. We have identified the following factors of the point generalisation problem:

Background vs. foreground data: We assume that our point data form the focus of attention, and hence represent the foreground. The background data are those acting as a base map, in the traditional cartographic sense. Background data provide a visual backdrop and spatial reference (e.g. giving hints to a mobile user to orient him-/herself), but in order to fulfil the role of spatial reference, they also impose spatial constraints on the points in the foreground.

Types of point data: We distinguish between two main types, called *points of interest (POI)* and *point collections (PColl)*, for the sake of simplicity (this distinction is of course a gross simplification, defining two ends of a spectrum). Examples of POIs include restaurants, museums, bus stops, or other address layer data; examples for PColls encompass any point data that exist in large collections, such as count data or categorical observations collected at point locations, animal observations, etc. POIs are, as the name suggests, of particular interest for a particular application, which also means that they are largely self-standing, existing on their own. Having said that, this also implies that POIs are more constrained in terms of spatial relations, such as topology. The Italian restaurant on the street corner must stay in this particular relation with the street network, even after generalisation, as it may also act as a landmark. Conversely, PColl data are representatives of collections of points and may be more liberally selected, aggregated, typified, displaced – as long as the overall spatial distribution of the point set is maintained. Finally, POIs typically have rich attributes associated, while PColls typically don't.

Constraints on point data: Background-foreground constraints — As mentioned above, the point data in the foreground are subject to spatial constraints by the background, or base map elements. Examples include *topological* relations, where a landmark POI should not switch sides of a road, or where a watershed may form a 'container' to mass points collected for that watershed. Besides topological constraints, the background also imposes other constraints on the point data, relating to the other two types of spatial relations commonly distinguished, *proximal* relations and *directional* relations (Jones 1997).
Foreground-foreground constraints — Constraints also act between the foreground objects themselves. We are dealing with point objects, and hence topological relations would seem irrelevant, yet they are relevant, since our points are in fact small area objects, owing to the fact that they are represented by cartographic symbols. And obviously, proximal and directional relations are also relevant.
Cartographic constraints — Maintaining the above spatial relations is one of the key mandates of any generalisation activity, and hence part of the standard set of cartographic constraints. Generalisation, however, also has to observe additional cartographic constraints relating to the structure, pattern, and semantics of point sets, such as density, spatial arrangement, or relevance ordering. Several typologies of cartographic constraints have been offered in the literature (e.g. Steiniger and Weibel 2007).

Level of interactivity: In mobile cartography (unlike in paper map production), it can be safely assumed that the user has the possibility – but also expects the system to deliver the capability – of interactively adjusting the map display, for instance, by zooming in/out, changing representations, switching on/of feature classes, drilling down on individual map objects. The higher the interactivity, the more can be adjusted and 'cleaned up' on the map (e.g. to resolve visual clutter by zooming), the more sub-optimal generalisation quality can be tolerated — but the higher also the expectations of the user regarding response times and real-time performance.

3 Algorithms for point generalisation

We propose to organise geometric algorithms for point generalisation on mobile devices into a hierarchical, three-level classification (fig. 1). The first level distinguishes the transformation focus: Transformations can either focus on the map objects (object-directed) or they can concentrate on a transformation of the map space (space-directed). On the second level, we distinguish the principle that is used to execute the generalisation transformations. The lowest level then lists the actual generalisation operations, which really only apply for the object-directed transformation focus.

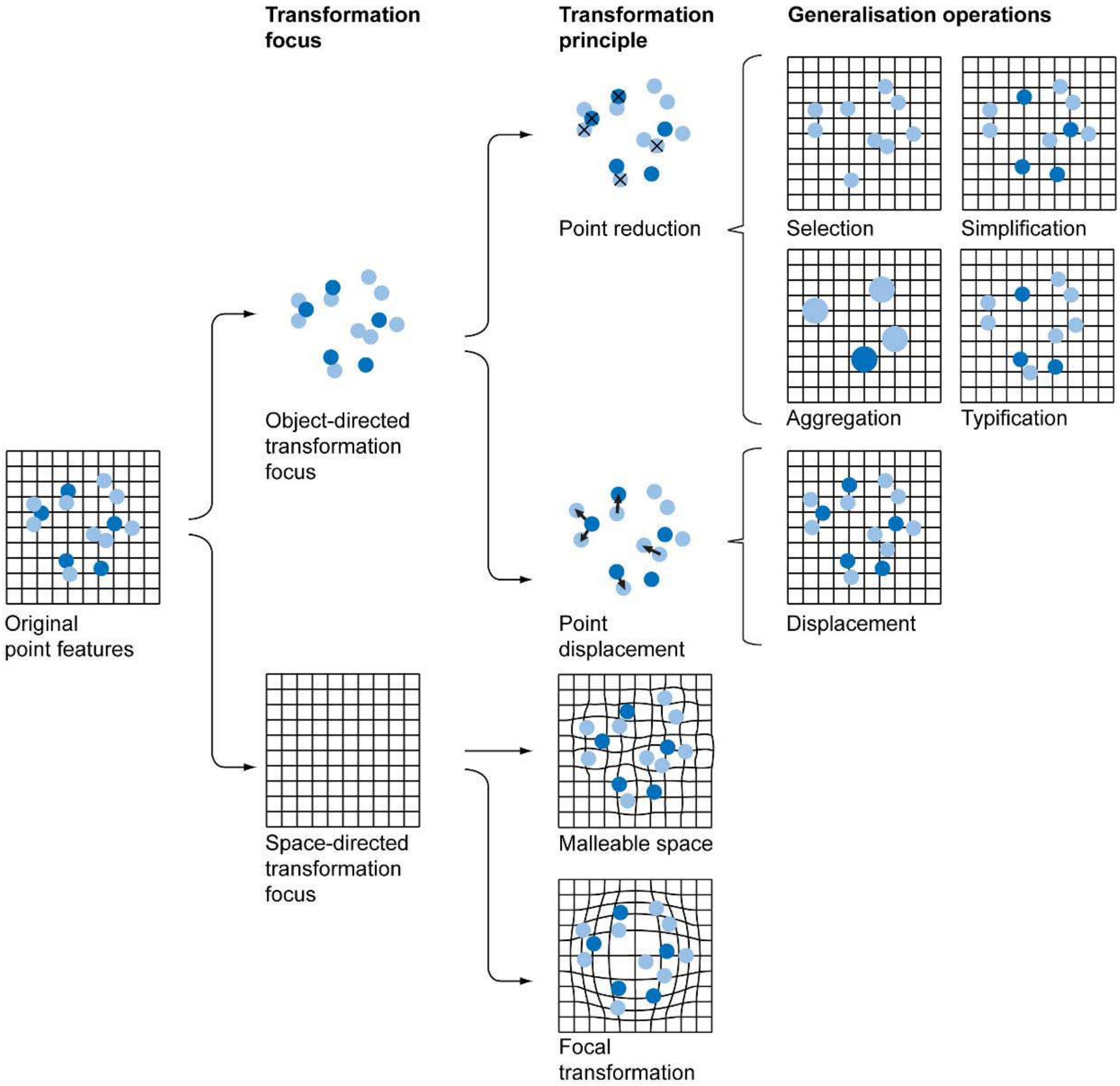

Figure 1. Geometric algorithms for point generalisation on mobile devices.

We have conducted an extensive review of the literature on point generalisation. However, in this paper, we will restrict the discussion to techniques with a high potential for real-time, mobile cartography. This favours simple and fast methods, as well as those that can be pre-computed and/or use hierarchical data structures. Algorithms relying on extensive spatial analysis and iterative optimisation are thus ruled out.

3.1 Algorithms with an object-directed transformation focus

Algorithms with an object-directed transformation focus modify the point objects without changing the metrical properties of the underlying spatial projection. This broad class represents the generalisation operations in the strict sense as termed in the generalisation literature. For each of these generalisation operators different algorithms are conceivable, some of which already exist in the literature. This section lists those with a potential for mobile mapping. Edwardes et al. (2005) define these five generalisation operations in detail, while we give only short descriptions. The working principle used by these operations to achieve the generalisation transformation is either point reduction or point displacements.

3.1.1 Point reduction

Point reduction algorithms reduce the number of points represented on a map as a function of the point density and the scale reduction factor applied. The assumption is that excess, unimportant points exist that need to be removed to make room on the map. Generalisation operations that use the point reduction principle include selection, simplification, typification and aggregation.

Selection: Select a subset of points from the original set of points, based solely on attribute, such as a relevance value per point object. Selected points remain at their original positions. The resulting number of points can be obtained from the Radical Law (Töpfer, 1974). Globally, selection is equivalent to a (simple and fast) filtering operation, primarily used to create a candidate set of points potentially involving conflicts that must be solved by other generalisation operations. Locally, selection may be used to select the more important of two overlapping point features (Edwardes et al., 2005).

Simplification: Like selection, simplification chooses a subset of the original points that remain at their original positions. However, it is governed by geometric properties such as proximity or density of points. The purpose of this operator is usually to relax the solution space for the conflicts rather than solve them entirely. The most trivial simplification algorithm would simply select points randomly. De Berg et al. (2004) describe algorithms for simplifying point patterns using ε-approximations (squares, rectangles) that aim to preserve density variation across the map space. Rather than using a uniform grid, hierarchical data structures such as quadtrees might be used that adapt to density variations (similar to Burghardt et al., 2004, who used quadtrees for aggregation).

Aggregation: Aggregation is the replacement of two or more point features with a new placeholder feature. Its main purpose is to reduce the level of detail in the map by grouping together semantically similar and spatially close points. In contrast to selection and simplification, aggregation generates new point locations. Aggregation has been implemented in two ways. First, by clustering algorithms (see Anders, 2003 for a review), where hierarchical methods provide the possibility for pre-computation and seem thus preferable (Mannes, 2004). Second, by hierarchical data structures including k-d trees, quadtrees (Burghardt et al, 2004) or reactive trees (van Oosterom, 1992).

Typification: Typification can be seen as a type of aggregation. However, it differs in that it uses the pattern of spatial relationships among a group of points to imply the existence of a new pattern that aims to carry the characteristics of the original point distribution. In order to get a grasp of the arrangement of point patterns, Delaunay triangulations have been used (Burghardt and Cecconi, 2007) or proximity graphs (Regnauld, 2001). Sester and Brenner (2004) provide an approach for continuous generalisation.

3.1.2 Point displacement

Displacement operates locally. It reconfigures point symbols in order to resolve conflicts by moving them apart, leaving their number intact. It is usually applied for the ‘finishing touches’, as the last in the chain of generalisation operators. Many displacement algorithms exist in the literature, but most rely on computationally demanding optimisation techniques and/or geometrically complex spatial analysis. Hence, only few algorithms remain that can potentially operate in a real-time environment, including an algorithm using the least disturbing space (Harrie et al., 2004) or metaphors of social relations to generate radial displacements (Mackaness and Purves, 2001). The greedy algorithm for energy-minimising ‘snakes’ may also be a possibility (Kass et al., 1987). Another very simple algorithm could be envisioned that would displace points to regularised grid locations. Given that mobile services are inherently interactive, we propose to also consider techniques relying on interaction, such as local radial displacement induced by mouse-over events.

3.2 Approaches based on a space-directed transformation focus

One of the key aims of map generalisation is to reduce spatial conflict, such as overlaps or congestion between map symbols. In principle, this can be achieved in two ways. Classical generalisation operators transform the map objects, keeping the map space fixed (we term this approach object-directed transformation). However, conflict can also be reduced by transforming the map space, while map objects are moved apart as a result of space deformation (space-directed transformation). The latter approach is a direct counterpart of feature displacement. For the space-directed transformation focus no generalisation operations are listed, as spatial conflicts are resolved by deforming the underlying space. Two transformation principles may be applied. First, focal projections (e.g. fisheye) deform the map space radially and globally from the map centre. Implementations have been shown by Harrie et al. (2002) and Rappo et al. (2004). The second principle adapts the space deformation locally to the existing map objects based on Laplacian smoothing using the dual mesh resampling by Taubin (2001). This approach has been advocated by Edwardes et al. (2005) and Edwardes (2007) and has the key advantage that both foreground and background objects are displaced together, maintaining spatial relations. However, for both space-directed transformations, the perceptual and cognitive validity remains to be evaluated.

4 A workflow and a research plan

4.1 Workflow overview

The focus for mobile maps today is shifting toward sustaining more interactive and dynamic interactions, owing to new interaction technologies such as touchscreens. We propose a problem-oriented workflow for point generalisation that addresses this shift, taking into account the dynamic and real-time nature of mobile environments considering the factors laid out in section 2 (§2). It is summarised in Table 1 and explained in detail below.

Workflow for Mobile Point Generalisation		
1.	Define resources	*Processing power, screen, bandwidth, user-interactions, background processing capabilities*
2.	Define purpose of the map	*Defines map purpose, map type, symbology (legend), content elements of the map (feature classes in back-/foreground), level of interactivity, and degree of filtering*
3.	Transformation focus	➢ Object-directed ➢ Space-directed
4.	Generalisation strategy	➢ Content conservative approach*: prioritises displacement operators* ➢ Balanced approach: *prioritises aggregation operators* ➢ Space conservative approach: *prioritises selection and typification operators*
5.	Execute generalisation	Choose generalisation algorithms; chain and apply algorithms

Table 1. Workflow for mobile point generalisation (text in italics is explanatory).

In the first step of the workflow the **available resources** are defined. These are not assumed to change throughout the generalisation process. Resources have an impact on the generalisation process changing cartographic constraints (e.g. minimal symbol size for interaction on touch screens) and the generalisation strategy applied. Resources include the mobile device (i.e. the client), background processing capabilities such as server-side services, and constraints of the human sensory system. Relevant resources for the mobile device are: screen resolution, processing power, local storage capacity, network bandwidth and user interface.

In a second step the **purpose of the map** is defined. What type of map visualisation is used and the message it should carry has not only an effect on the visual appearance of the map but also defines to a certain extent how the generalisation process is conducted. Therefore different elements play a role: the available resources, the user, his/her given task, and the mobile context. These elements influence the factors for point generalisation, hence the type of the point data (POI or PColl),the importance of background or reference data, the constraints on point data, and the level of interactivity.

The purpose of the map informs how the map should reflect information, whether using an object-directed or space-directed transformation focus and whether the information is better generalised using a content conservative approach, a spatially conservative approach or rather a balanced approach.
Note that steps 2 to 5 depend on the requirements of a particular user and will therefore change and/or re-run depending on user and map purposes. An example for using a space-directed approach would be a map for a tourist wandering around Zurich. Here the relative positions of landmarks immediately around him/her are of greater importance than unreachable ones. On the other hand, if the very same tourist requests a map to understand the spatial distribution of the fox population in the City of Zurich (there are indeed a great number of 'city foxes' in Zurich), an object-directed transformation focus with a content-conservative generalisation strategy may be of better use.

The **transformation focus** defines whether to select an approach based on an object-directed or space-directed transformation focus. The applied algorithms solve spatial conflicts by either deforming the map space or transforming feature points on the map space. Note that the different transformation foci and principles are not mutually exclusive; they merely represent solutions to the same problem (unambiguously placing map symbols on scarce map space) and can possibly be mixed.

The **strategy for point generalisation** defines how spatial conflicts are resolved:

- The *content conservative approach* tries to retain as many point features as possible on the map and prioritises displacement as a generalisation operator. It assumes that the point features have been previously filtered to a sufficiently small number.
- The *balanced approach* resolves spatial conflicts by aggregating point features and is better suited for highly interactive maps that need a larger 'interaction footprint' per point feature.
- The *space conservative approach* tries to avoid displacement of point features and prioritises selection and typification as generalisation operators.

The strategy then defines how the actual **generalisation** is implemented and **executed**. This includes the choice of algorithms (on-the-fly or pre-computed data structures), execution of attribute transformations, filtering, and chaining and execution of generalisation operations.

4.2 Research plan

We plan to implement and validate the proposed workflow and its elements on the basis of use cases and user experiments. The following research questions will be addressed:

- Which algorithms for point generalisation have potential for real-time execution?
- How do the different strategies for point generalisation affect map reading tasks (in terms of efficiency and accuracy)?
- How useful and usable are the generated displays?
- How is the cartographic quality of the results evaluated by cartographers vs. lay users?

In a first phase, we plan to compare candidate algorithms against each other to assess their capability to operate in real-time. This selection will be based on the theoretical analysis of the literature as well as on performance tests in a typical mobile setting (knowing that the technology changes fast). A second phase will focus on an empirical evaluation of the efficiency and effectiveness (i.e. accuracy) with which users can solve given tasks derived from use cases, using different generalisation operators and strategies. Task efficiency and task accuracy will serve as proxies for assessing the *usefulness and usability* of the generated displays. In the same phase, an evaluation of the *cartographic quality* of generalisation results by experts (i.e. cartographers) vs. lay users will be conducted. The user studies are also expected to provide hints on preferred transformation foci and generalisation strategies with respect to certain use cases (i.e. map purposes). Finally, in a third phase the overall workflow is planned to be evaluated in another user study.

5 Conclusions and Outlook

This paper delivered three things: We defined the problem of point generalisation in mobile mapping; we extended the typology for point generalization operators and categorised and reviewed different algorithms for mobile point generalisation; and we proposed a workflow for point generalisation in mobile environments.

The extension of the typology for generalisation operators (AGENT, 1998; McMaster, 1987a,b) introduces a space-directed transformation focus to the existing object-directed approaches. It also bridges between two aspects of how generalisation can be looked at, from a strictly object-directed or space-directed point of view, and it allows integrating algorithms that deal with spatial transformation into the generalisation process.

This distinction feeds into a workflow for mobile point generalisation that furthermore considers the trade-offs between content- and space-conservative strategies for generalisation defined by the map purpose. Given a clear map purpose (such as planning, orientation or exploration), the transformation focus and generalisation strategies can be defined and conducted.

Finally, we have provided the plan of our future research to put in place and evaluate the proposed generalisation workflow and its algorithms.

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