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Various applications, ranging from map creation tools to navigation systems, employ methods introduced by the domain of georeferencing, which investigates techniques for uniquely identifying geographical objects. This paper aims to provide an overview of ongoing challenges of the georeferencing domain by presenting, classifying and exploring the field and its relevant methods and applications.

Keywords: georeferencing; map matching; road network matching; location referencing; conflation; registration

1. Introduction

Georeferencing can be seen as an umbrella term for techniques which are concerned with the unique identification of *geographical objects*. The term 'geographical object' in a broader view refers to any kind of object or structure which can reasonably be related to a geographical location, such as points of interest (POIs), roads, places, bridges, buildings or agricultural areas. A *geographical location* is an entity which represents a spatial reference. Geographical locations can be defined in multiple spatial dimensions: 0-dimensional (points), 1-dimensional (lines), 2-dimensional (areas) and, rarely, 3-dimensional (bodies). For example, POIs can be referenced to 0-dimensional point locations, while road segments can be referenced to line locations. Buildings, even if they are represented as 3-dimensional models, are usually referenced to 2-dimensional area locations, since they are assumed to stand on the ground level.

Hill (2006) distinguishes between *informal* and *formal* means of referring to locations. *Informal* georeferencing describes colloquial references to geographical objects such as place names, while *formal* georeferencing covers the domain of exact location referencing in science and technology, e.g. using spatial reference systems. Throughout this paper, we will focus on investigating formal georeferencing techniques.

There are various definitions for the term 'georeferencing'. For example, Sommer and Wade define georeferencing as 'aligning geographic data to a known coordinate system so it can be viewed, queried, and analysed with other geographic data' (Sommer and Wade 2006). Coarser views include the domain of georeferencing multimedia (Zheng, Zha, and Chua 2011) and the exploration of means for the identification of geographical objects in general.

Generally, three distinct types of information can be identified which can be used to reference geographical objects.

(1) Geometrical information describes geometric properties of an object, such as the layout and shape of a road segment.
(2) Topological information deals with properties which are preserved under continuous deformations of objects; in the context of georeferencing, the graph structure induced by networks of certain geographical objects, such as roads or rivers, is of primary concern for topological investigations.
(3) Semantic information includes various kinds of semantic properties which can be related to a geographical location, such as the name of a place or road. Common methods of georeferencing consider at least one type, but often a combination of these types of information in order to uniquely identify a geographical object.

The process of identifying geographical objects and assigning them to geographical locations is called *matching*. When a map is authored from scratch, the author defines geographical objects, locations as well as assignments between them. Georeferencing usually takes place using a geodetic reference system such as *WGS-84* (National Imagery and Mapping Agency 2000), which

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comprises a standard coordinate frame for the Earth, a reference ellipsoid and a geoid which defines a nominal sea level. Other reference systems may also be adopted depending on specific application fields. To some extent, navigation devices can be used for data collection within a map-making process. GPS trackers deliver coordinates within the WGS-84 geodetic reference system which can be related to a certain geographical reference on a map. However, often the process of assigning objects to locations is nontrivial. The different types of geographical objects to be matched on a map range from raster images such as aerial or satellite imagery to entities on pre-authored digital vector maps. Depending on the type of matching required, various kinds of methods and algorithms have evolved. Section 3 gives a classification of matching types and introduces appropriate methods for dealing with these matching problems.

The outcome of a matching process is an assignment between geographical objects and geographical locations. Often, the object to be referenced on a certain map originates from another map with its own geographic reference system. In this case, a matching delivers correspondences between these two maps which express commonalities as well as differences, i.e. the information which objects could and which could not (or only partially) be identified on both maps.

The combination of map data from several sources in order to create a new map is called *conflation*. Longley et al. (2005) define conflation in the context of geographic information systems as 'the process of combining geographic information from overlapping sources so as to retain accurate data, minimize redundancy, and reconcile data conflicts'. Conflation is performed by using matching strategies for different structures (often nodes, segments and edges) to identify correspondences between maps in order to correlate and combine the data into a new map. According to a classification approach proposed by Yuan and Tao (1999), conflation can be divided into *horizontal* (combining neighbouring areas) and *vertical* conflation (combining different maps of the same area). While horizontal conflation is usually done between vector maps, vertical conflation may also be performed between raster–vector or vector–raster pairings of maps (Zhang 2009).

2. Problems and methods in the georeferencing domain

2.1. *Georeferencing of raster images*

A common problem of the georeferencing domain involves assigning certain objects contained in raster images to location references. This is performed by employing methods and techniques from several fields, ranging from remote sensing and photogrammetry to computer vision, image processing and pattern recognition.

Raster imagery depicting a geographical area is often obtained via satellite or aerial photography. Raw images are pre-processed and orthorectified (geometrically corrected) in order to eliminate distortions, e.g. caused by camera tilt, topographic relief or optical properties of the lens. The processed images are then partitioned into multiple segments according to segmentation algorithms, such as edge detection (Lindeberg 2001), region growing (Adams and Bischof 1994) or split and merge (Douglas and Peucker 1973). Identified segments are further processed via feature extraction, which applies a dimensionality reduction in order to facilitate a classification of objects being shown in the image (Guyon and Elisseeff 2003). This way, subsets of pixels can be classified according to categories such as 'road' or 'farmland' using an appropriate *classifier* (classification algorithm) for the given features.

In order to georeference raster images, they are connected to digital maps via so-called *ground control points* (GCPs) (De Leeuw, Veugen, and Van Stokkom 1988). GCPs are landmarks located at a well-known position which are chosen so that they can easily be identified in satellite or aerial imagery, such as road crossings or artificial targets. Since orthorectified images are of uniform scale, it is sufficient to correlate several (at least three) GCPs to sets of pixels within an image which have been classified accordingly. This way, the remaining pixels and also other identified features and objects can be georeferenced to positions on a map. GCPs may be pre- or postmarked; premarking involves marking control points with targets before flight, while in the process of postmarking, GCPs are selected after the flight based on natural image features which are deemed most suitable for this purpose. (US Army Corps of Engineers 2002) Depending on whether a GCP is used for horizontal or vertical referencing, differently shaped artificial targets or natural features may be appropriate. Premarking provides an expansive means to identify locations in relatively featureless terrain, while postmarking has the advantage that a GCP can be chosen in the optimum location. However, natural features are not as well defined as artificial targets.

2.2. *Georeferencing of vector data*

Georeferencing vector data involves finding an assignment between a vector and a corresponding element within a digital map. In the simplest form, a coordinate pair must be assigned to a certain map. This problem is known as *positioning* or *map matching*. Often, the given coordinates are subject to a varying level of inaccuracy, e.g. when they are obtained from consumer-grade GPS devices. Thus, certain filtering, rectification and validation must be put in place in order to match coordinates on a map. For example, a map matcher working on a navigation device used for street navigation must obey the constraint that a valid position may only be located on a road segment.

The process of georeferencing complex vector data which may also possess a spatial extent, such as a line, an area or a road network, to a vector map is called *location referencing*. For example, the term *point location* refers to POIs such as a bus stop, while the term *line location* describes a sequence of (road) segments which comprise a route, e.g. from one city to another.

Location referencing can be done statically or dynamically (Schneebauer and Wartenberg 2007). Static location referencing approaches such as the European Traffic Message Channel standard (TMC) (ISO 14819-1 2003) or the Japanese Vehicle Information and Communication System standard (VICS) (Yamada 1996) use predefined location codes or lookup tables in order to uniquely identify locations on a map. In contrast, dynamic location referencing techniques such as ISO 17572-3/AGORA-C (Wevers and Hendriks 2005), the improved AGORA-C variant proposed by Xi (Xi, Weifeng, and Tongyu 2008), OpenLR (TomTom International B.V 2012), TPEG-LOC (CEN ISO/TS 2006), MEI-LIN (Wartenberg 2008) or TPEG-LOC2/ULR (Fraunhofer FIRST 2012) aim to provide a location referencing scheme which describes a location in a 'map-agnostic' way, i.e. without employing hard-coded references to segments or nodes of a certain map. Thus, locations encoded using dynamic location referencing approaches can be decoded and referenced on any map which offers sufficient topological and geometrical similarity to the map used in the encoding process.

For the problem of georeferencing an entire road network (rather than, e.g. a line location) to another vector map of the same area, the term *Road network matching* has been coined (Diez, Lopez, and Sellarès 2008). Road network matching investigates the similarities between the road networks of the maps to be matched (usually two), thereby suggesting a mapping from the set of road segments in the first (source) map to the set of road segments in the second (destination) map. The mapping between segments may be of 1:1 type in the simplest form, but also 1:*n*, *n*:1 and *m*:*n* type mappings may be needed to accurately describe correspondences between road segments of the maps.

In order to deal with the complexity involved with *m*:*n* type mappings, approaches have been proposed which aim to find correspondences on higher levels of abstraction. For example, Qian, Qiang, and Min (2011) suggest a reduction of the road network to so-called *strokes* which are derived from the road network. Mappings can then be investigated on the stroke level, rather than on the level of individual segments or nodes.

3. Taxonomy of georeferencing methods

Georeferencing can be seen from different perspectives. It may be classified by type (vector or raster referencing), by identification category (semantic, topological or geometrical) and by application scenario. Classification by type approaches the domain from a structural perspective which focuses on the organizational methods employed for recording and referencing geographic data. In contrast, classification by identification category can be seen as being orthogonal to the former, as it classifies the domain with respect to mathematical categories of properties used for the unique identification of geographical entities. Finally, while these two classification approaches maintain a technical perspective, classification by application scenario provides a means of organizing the georeferencing domain from a holistic, application-oriented point of view.

3.1. Classification by type

Georeferencing can be divided into two types: *vector* and *raster referencing*. Figure 1 shows a classification approach of the types of georeferencing.

3.1.1. Vector referencing

Vector referencing deals with identifying locations which can be described by means of vectors. It can further be divided into *point referencing*, *location referencing* and *road network matching*. Point referencing is the unique identification of a geographical point location, e.g. given by its WGS-84 coordinates, in a reference frame. In order to identify a position on a digital map, a projection from the input space (such as GPS sensor raw data or an object in a raster image given by a set of pixels) into the reference system of the digital map must take place. While the term location referencing usually refers to the identification of routes consisting of sequences of vectors (e.g. road fragments) or polygons defining areas, road network matching is concerned with finding correspondences between graphs induced by the road networks of different maps (see Section 2.2).

3.1.2. Raster referencing

Raster referencing is concerned with the problem of correlating pixels contained in raster images with geospatial references. In detail, it involves a projection of features between two geospatial reference frames, where at least one feature space is composed of sets of pixels from raster image data (see Section 2.1). Depending on the desired direction and pairing type (vector-to-raster, raster-to-vector or raster-to-raster), different methods must be employed to find suitable correlations. The domain of *image registration* is concerned with finding appropriate transformations between images, enabling mappings between different coordinate systems.

3.2. Classification by identification category

There are three categories of properties which may be used to uniquely identify geographical entities:
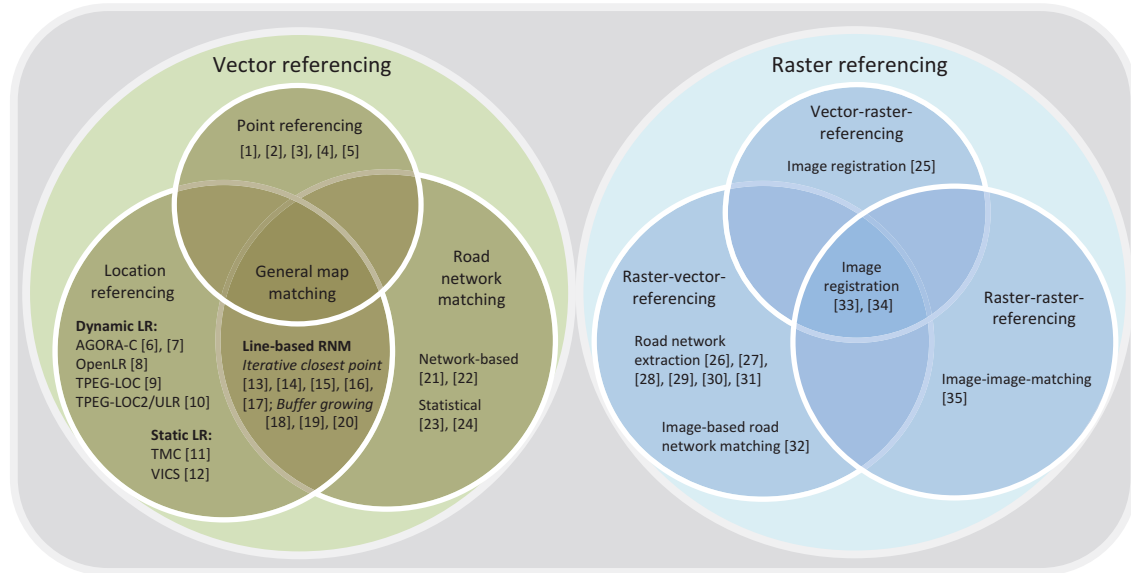
Figure 1.   Types of georeferencing. Numbers in square brackets indicate source details to references which are as follows: [1], Quddus, Ochieng, and Noland (2007); [2], Quddus et al. (2003); [3], Ochieng, Quddus, and Noland (2009); [4], Lakakis et al. (2004); [5], Quddus, Ochieng, and Noland (2006); [6], Wevers and Hendriks (2005); [7], Xi, Weifeng, and Tongyu (2008); [8], TomTom International B.V. (2012); [9], EBU_B/TPEG (2002); [10], Fraunhofer FIRST (2012); [11], ISO 14819-1 (2003); [12]Yamada (1996); [13], Rusinkiewicz and Levoy (2001); [14], Besl and McKay (1992); [15], Gösseln and Sester (2004); [16], Gösseln (2005); [17], Volz (2006); [18], Walter (1997); [19], Mantel and Lipeck (2004); [20], Zhang and Meng (2007); [21], Xiong and Sperling (2004); [22], Xiong (2000); [23], Walter and Fritsch (1999); [24], Zhang, Yang, and Xuechen (2012); [25], Kovalerchuk et al. (2008); [26], O'Donohue (2010); [27], Poullis and You (2010); [28], Péteri, Celle, and Ranchin (2003); [29], Tien, Xiao, and Qin (2008); [30], Mokhtarzade and Zoej, 2007; [31], Gruen and Li (1995); [32], Zhu et al. (2009); [33], Zitová and Flusser (2003); [34], Brown (1992); [35], Christmas, Kittler, and Petrou (1994).

topological, geometrical and semantical. Figure 2 shows a classification of these identification categories.

3.2.1.   Topological properties

Topological properties are properties which are preserved under continuous deformations of objects. The most important objects present in digital maps with respect to topological investigations are structures which induce a graph, such as road networks. The fact that topological properties are agnostic of geometrical deviations between two maps facilitates the use of topology to identify geographical entities within different maps regardless of minor differences in shape, position or other geometrical properties. However, maps originating from different vendors may reveal major topological differences, e.g. regarding the modelling of crossings. Examples for topological properties include the number of roads joining a crossing (valence of the node of the induced graph) as well as the existence of subgraph isomorphisms (Wartenberg 2008) or the clustering coefficient (Soffer and Vásquez 2005). Also, the adjacency of polygons may be used to characterize geographical entities.

3.2.2.   Geometrical properties

Geometrical properties describe the geometry of an object. Various geometrical parameters can be used to identify geospatial entities. For example, point locations are identified via their coordinates, while line locations are given by their geometrical shape. When dealing with polygons, other properties such as the covered area provide an additional means for referencing. If the georeferencing process involves the conflation of different maps containing objects which share geometrical properties, relative metrics such as the Hausdorff distance (Yuan and Tao 1999; Alt and Guibas 1999) are criteria for proper referencing of objects. As geographical databases exhibit a varying precision of geometrical records, geometrical properties of objects should not be used as a single means of identification.

3.2.3.   Shared geometrical/topological properties

Some properties share geometrical as well as topological aspects. For example, point objects located on a road network may be identified via the angles of incident edges, as it is done by the spider function (Saalfeld 1988), which calculates an index assigned to node based on the quantization of these angles into sectors.
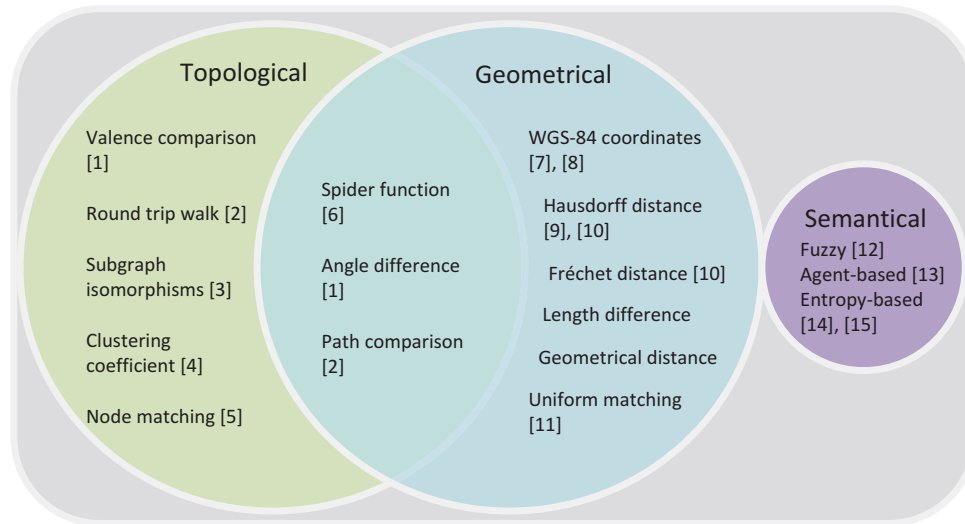
Figure 2. Identification categories. Numbers in square brackets indicate source details to references which are as follows: [1], Xiong (2000); [2], Filin and Doytsher (2000); [3], Wartenberg (2008); [4], Soffer and Vásquez (2005); [5], Xuan et al. (2012); [6], Saalfeld (1988); [7], National Imagery and Mapping Agency (2000); [8], Boucher and Altamimi (2001); [9], Yuan and Tao (1999); [10], Alt and Guibas (1999); [11], Veltkamp and Hagedoorn, 2001; [12], Foley and Petry (2000); [13], Rahimi et al. (2002); [14], Walter and Fritsch (1999); [15], Vosselman (1992).

3.2.4. Semantic properties

Semantic properties, in general, are all properties which determine the meaning of an object. In digital maps, all information not falling into the geometrical or topological category can be considered semantical. This includes data such as the names of places, streets or POIs, street numbers, speed limits posted on road segments, the importance of a segment within the road network, etc. Semantic information is often useful for identifying geographical entities, since, for example, street names found on digital maps rarely match within a small geographical area if they do not represent the same street. However, it should never be used as a single means of identification, since large differences in semantic attributes must not necessarily imply that different entities are described. For example, there are various ways to spell a street name and also, sometimes, multiple street names for the same street. The extent to which semantic attributes are recorded as well as their quality greatly varies between different maps. Several approaches have been proposed for dealing with the fuzziness of semantic properties, notably using fuzzy logic (Foley and Petry 2000), agents (Rahimi et al. 2002) as well as information entropy (Walter and Fritsch 1999).

3.3. Classification by application scenario

Most applications of georeferencing techniques fall into one of the following categories: map manipulation, map creation, map validation, map matching and georeferencing of media. Figure 3 shows a classification of the application scenarios of the georeferencing domain.

3.3.1. Map manipulation

Map manipulation is the process of altering certain objects in maps. This may be required to correct errors present in a map which can be detected using map validation. As a result of a conflation process (Xiong 2000; Ruiz et al. 2011), additional attributes such as POIs can be merged into a map. Incremental updating is used in order to only replace those parts of a map which have changed in a more recent version, which can be derived via change detection. The problem of incremental updating is of rising concern to the automotive navigation industry (Basiaensen 2003; Scheu, Effenberg, and Williamson 2000).

3.3.2. Map creation

Maps may be authored from scratch, for example, by creating geographical entities and references based on satellite or aerial imagery (see Section 2.1) or highly accurate GPS traces (Kurihara, Nonaka, and Yoshikawa 2004). Another option is to create maps by combining two or more source maps into a new map using conflation methods (Xiong 2000; Ruiz et al. 2011). In general, it is possible to create visualizations of any data possessing spatial references (Pundt and Brinkkötter-Runde 2000).

3.3.3. Map validation

Map validation is concerned with evaluation of certain properties in maps, such as geometrical correctness or the presence of a normal form with respect to certain topological properties. Quality metrics used to assess a
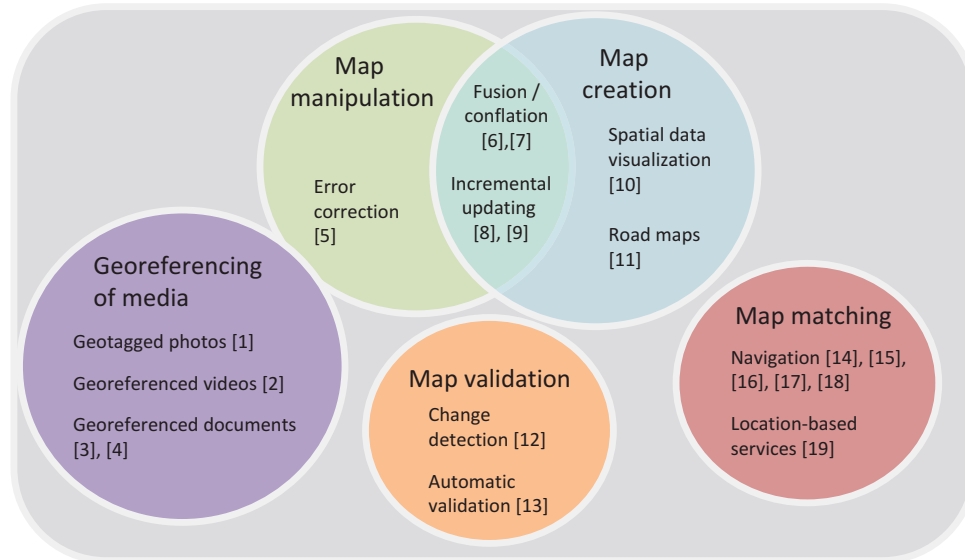
Figure 3.   Application scenarios. Numbers in square brackets indicate source details to references which are as follows: [1], Snavely, Seitz, and Szeliski (2006); [2], Zheng, Zha, and Chua (2011); [3], Hao (2010); [4], Mani et al. (2010); [5], Maras et al. (2010); [6], Xiong (2000); [7], Ruiz et al. (2011); [8], Basiaensen (2003); [9], Scheu, Effenberg, and Williamson (2000); [10], Pundt and Brinkkötter-Runde (2000); [11], Kurihara, Nonaka, and Yoshikawa (2004); [12], Zhang and Couloigner (2005); [13], Xiong and Sperling (2004); [14], Quddus, Ochieng, and Noland (2007); [15], Quddus et al. (2003); [16], Ochieng, Quddus, and Noland (2009); [17], Lakakis et al. (2004); [18], Quddus, Ochieng, and Noland (2006); [19], Rao and Minakakis (2003).

map can be derived by detecting and evaluating changes. For example, regression errors may be identified using change detection (Zhang and Couloigner 2005). Automatic validation (Xiong and Sperling 2004) aims to validate a map according to such quality metrics without the need for assistance provided by a human operator.

3.3.4.   Map matching

Matching a point on a vector map is a requirement for navigation (e.g. for cars or pedestrians). Also, other applications needing exact positioning, such as location-based services, rely on map matching in order to identify the position of the user on a map.

3.3.5.   Georeferencing of media

Zheng, Zha, and Chua (2011) describe various applications for enhancing media (photos, videos and documents) with geographical references, which are often encoded as WGS-84 coordinates. For example, photo layers for services such as Google Earth provide the user with crowd-sourced geo-tagged imagery of millions of locations around the globe. Snavely, Seitz, and Szeliski (2006) introduce a method for determining the exact position of images in three-dimensional space, including the angle of the camera, which enables the 3-dimensional exploration of photo collections. Also, videos and travel logs may be georeferenced in order to associate them with geographical locations where a video was shot or the author of a

travel log has been. Spatial markup languages such as SpatialML (Mani et al. 2010) allow for embedding spatial references into natural language documents.

4.   Conclusion

4.1.   Summary

In this paper, we have provided an overview of the georeferencing domain. Following a general definition of georeferencing and associated concepts, the characteristics of various problems and methods in the field have been identified.

We then classified georeferencing in a more detailed fashion, using three different perspectives. The first perspective distinguishes existing methods by the type of reference, namely vector and raster based. Secondly, a classification based on the identification category used for establishing a spatial reference (topological, geometrical and semantical) was introduced. Finally, georeferencing was classified by application scenario, which includes map-focused applications as well as geographic referencing in media. The different perspectives allow for a quick understanding of georeferencing for readers with different backgrounds, ranging from those familiar with GIS applications, conflation and image registration to those with an application-oriented focus, e.g. from the navigation industry. While several research communities have their own definition for georeferencing, we believe that the holistic view

presented in this paper provides a balanced overview of the domain that considers all relevant areas.

4.2. Outlook

Future research of georeferencing will be guided by the requirements of growing geographical information services. With the increasing availability of digital geospatial information, georeferencing methods have to deal with a higher number and variety of sources at more different levels of granularity. Approaches are necessary, for example, to improve map-agnostic location referencing algorithms for automotive applications and robust map validation and to integrate volunteered geographical information (VGI). With the advent of indoor navigation applications, a new set of fine-grained georeferencing methods is needed to associate real-world entities with geographical locations.

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