Towards an Analytical Framework for Enriching Movement Trajectories with Spatio-Temporal Context Data

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Abstract

Although there are numerous studies in which movement trajectories were analysed based on their geometry alone, a more holistic interpretation requires their contextual setting to be incorporated into the analytical process as well. Among other influences, for instance, several attributes of the underlying physical space can have an effect on movement. Thus, a critical task is to semantically enrich movement trajectories with attribute values derived from one or more underlying raster layers with spatio-temporal data. This process, however, is not always trivial due to the fact that currently, there exists no comprehensive framework or toolset for such purposes. Further, communicating the exact procedure which was used in a study is impeded by a lack of formal terminology required to unambiguously define the involved methods and operators. In this paper, we address these issues and conceptualize an analytical framework for the process of enriching movement trajectories with spatio-temporal context data from underlying raster layers, as well as propose a terminology to explicitly define the spatio-temporal scope of the analysis. We demonstrate the validity of our concept on a practical example.

Keywords: semantic trajectory, annotation, map algebra

1 Introduction

Numerous studies have analysed movement data in order to examine characteristics, patterns and dynamics of movement and the moving entity. Frequently, such work has focused on analyzing the geometry of the trajectory, while ignoring its contextual setting (Laube 2014, Demsar et al. 2015). In fact, however, movement is always set in context, which can involve the underlying physical space, the time, static or dynamic objects, or events (Andrienko et al. 2011). For this reason, the prevalent context-independent view on trajectories has been identified as one of the major pitfalls of movement analysis (Buchin et al. 2012). As a reaction, there has been work on enriching raw trajectories with context information in order to create semantic trajectories, which allow for detecting relations between movement and its contextual setting (Spaccapietra and Parent 2011, Andrienko et al. 2011).

In this research, we focus on the semantic enrichment of trajectories, and explicitly on annotating raw movement data with attributes of the physical environment, as derived from external data sources. In practice, the most common approach for this is to overlay a trajectory with context data, often in the form of separate raster layers, and annotate each point of the trajectory with the underlying cell value (cf. Buchin et al. 2012).

In many cases, however, this procedure is not sufficient. Rather than treating each position fix separately, it can make sense to view them as parts of larger meaningful units, such as all positions recorded while walking to work, or within a certain time interval, and in some way combine their underlying cell values for the analysis (e.g. to identify the maximum temperature a person was exposed to during a walking trip). Further, allocating a cell (and its value) to a position fix based on their locational equivalence is highly sensitive with regards to possible positional inaccuracies of the movement data and the spatial resolution of the context data. Therefore, for some scenarios, it can be more appropriate to choose an approach which takes not just one, but a combination of several neighboring cells into account (e.g. calculate the average of all temperature values of cells within 50 meters of a position fix). Furthermore, a context dataset typically represents a static snapshot of a dynamic environmental attribute, e.g. the temperature recorded at a certain point in time. Often, though, this particular instant will not completely correspond to the time at which the movement took place. In such cases, it can be worthwhile to extend the temporal scope of the analysis to combine several datasets with different time stamps (e.g. combine the temperature values recorded in a certain time window around a position fix).

Currently, despite the fact that conceptual frameworks for general semantic trajectory annotation have been proposed (e.g. Andrienko et al. 2011), the specific process of annotating movement trajectories with underlying spatio-temporal context data is still a challenging task. There exists no comprehensive framework or even a toolset to be used for these purposes, especially with regards to more complex application scenarios, as briefly outlined before. Further, communicating the exact procedure used in a study is impeded by the lack of a formal terminology to unambiguously define the involved methods and operators.

In this paper, we address these issues and conceptualize an analytical framework for the process of enriching movement trajectories with spatio-temporal context data from underlying raster data layers. Drawing heavily from Tomlin's (1990) map algebra and follow-up work (e.g. Laube et al. 2007), we propose a terminology to explicitly define the spatio-temporal scope of the analysis at the trajectory as well as the context data level. We implement our framework and demonstrate its validity on a practical example.

This paper is structured as follows: first, background information is provided on movement data and its semantic annotation, as well as the concept of map algebra. Then, our framework is presented and tested in an exemplary application. Finally, the results are discussed and the paper is concluded.

2 Background

2.1 Movement Data

Intuitively, the movement of an entity, e.g. a person, involves a change in its physical position based on a reference system such as geographical space (Andrienko et al. 2008). Various types of sensors, including Global Navigation Satellite Systems-based positioning (GNSS), can be used to record this movement in the form of series of chronologically ordered *x*, *y*-coordinate position fixes with a distinct *id* and enriched with a time stamp *t*:

$$pos\ fix_i = (id_i, t_i, x_i, y_i) \tag{1}$$

Since these position fixes are chronologically ordered, it is possible to determine for each individual fix its immediate neighbours as a sub-sequence of position fixes *P* recorded within a certain time interval (t_s, t_e), using a sliding window *W*:

$$[W]_{t_e}^{t_s} = \{pos\ fix_i \in P \mid t_s \leq t_i \leq t_e\} \tag{2}$$

Apart from sliding time windows, one can also create meaningful sub-sets of position fixes, which Spaccapietra and Parent (2011) refer to as a trajectory, e.g. all movements recorded on a certain day:

$$trajectory_j = \left(id_j, \{pos\ fix_i, \ldots, pos\ fix_n\}\right) \tag{3}$$

The entirety of recorded movements for a moving entity, finally, is called a movement track by Spaccapietra and Parent (2011), and includes all recorded trajectories:

$$track_k = \left(\ mover\ id_l, \{trajectory_j, \ldots, trajectory_n\}\right) \tag{4}$$

2.2 Setting Movement Data in its Environmental Context

When analyzing the movement behavior of humans or animals, various information can be extracted from a geometrical analysis of the raw movement data, such as the speed, direction, sinuosity, stationary locations and many more (cf. Laube 2014). For a more holistic interpretation of movement behavior, however, the contextual setting should be incorporated into the analytical process (Demsar et al. 2015). From the various types of context, this study puts its focus on attributes of physical space, which includes for instance the underlying topography (e.g. Cagnacci et al. 2011), the wind speed and direction (e.g. Shamoun-Baranes et al. 2012), the temperature (Andrienko et al. 2008), or ocean currents (Block et al. 2011), all of which can have an influence on the observed movement behavior.

Such information on the environmental context can either be derived from external datasets, e.g. temperature or slope raster layers, or simultaneously collected from various mobile sensors (Demsar et al. 2015). With regards to the former option, which is in the focus of this study, the raw movement data is typically annotated based on a spatio-temporal correspondence of the recorded position fixes and the underlying raster cells. For instance, Buchin et al. (2012) identify as a trajectory’s context the sub-set of cells from one or more raster layers which directly underlie its position fixes, Block et al. (2011) calculate marine species hotspots from trajectories and relate them to oceanographic variables in the underlying grid cell, and Andrienko et al. (2011) link movement events to context elements based on their spatio-temporal position. To the best of our knowledge, however, there is currently no comprehensive framework or toolset, which would be applicable to more complex spatio-temporal analyses, as outlined in the introduction.

2.3 Map Algebra

Map algebra, proposed by Tomlin (1990), describes a formal system of arithmetic operations in a grid-based cartographic model, and aims to generalize and standardize the related analytic functionalities of GIS. A map algebra statement is typically in the form of:

$$outputlayer = function(inputlayers) \tag{5}$$

The function takes as input one, two or more layers, but always produces one distinct output layer. The value processing functions can be arithmetic, statistical or logical, always depending on the spatial scope of the analysis (Albrecht 2007, Tomlin 1990). These include e.g. a *local* operation, which focuses on values from the same cell or single location at a time, whereas a *neighbourhood* operation combines a value from a location with a sub-set of locations within its direct vicinity. In contrast, *zonal* operations divide their input into zones based on homogeneous cell values, and finally, *global* operations take all cells of a layer into consideration (Tomlin 1990).

Today, map algebra has been conceptually extended in various ways. Especially relevant for our work is a study by Laube et al. (2007), in which the authors describe local (instant), focal (interval), zonal (episode), and global operators for defining the scope of the computation of context-independent movement parameters such as the speed or the sinuosity.

3 Concept

The proposed framework transfers the fundamentals of map algebra to the context of semantic trajectory annotation.

Initially, we have a track, as a collection of position fixes, and one or more underlying context raster layers with values to be annotated to the position fixes.

As a first step of the annotation process, its spatio-temporal scope is defined, both with regards to the movement data and the involved context data. For this, we refer to Tomlin's context operators, our interpretation of which is listed in table 1 and visualized in figure 1.

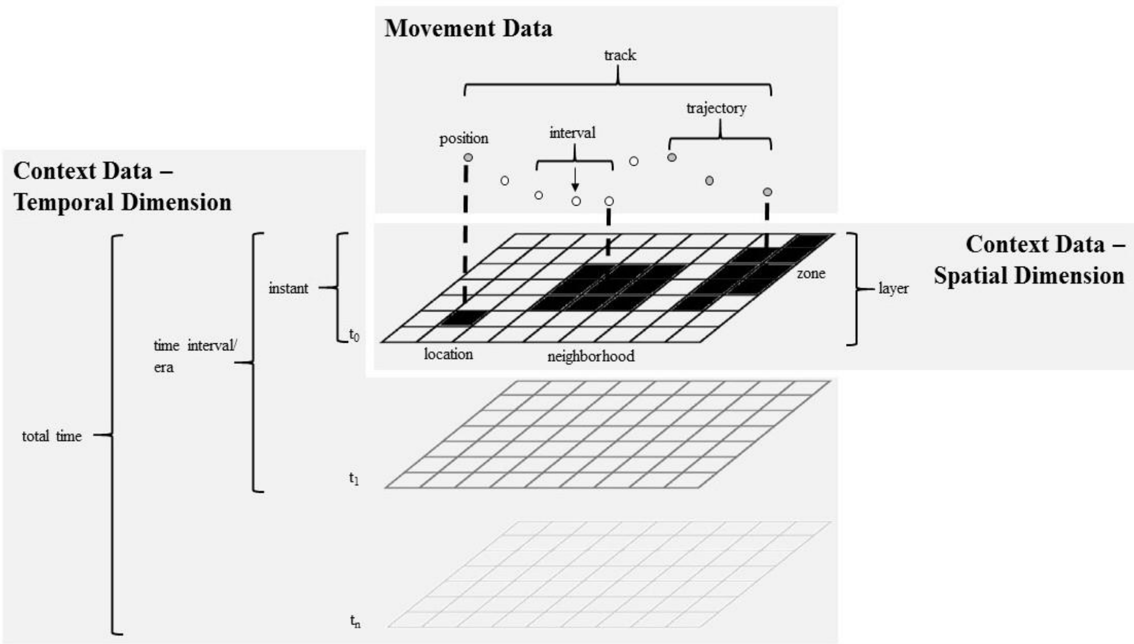
With regards to the analytical scope of the movement data, based on Spaccapietra and Parent (2011) and Laube et al. (2007), we denote an elementary, point-like position recording as a *position*. An *interval* is a sub-set of positions based on a moving window of fixed temporal duration (e.g. all temporal neighbors recorded 15 minutes before or after a position), and a *trajectory* a semantically defined segmentation of a track (e.g. all positions recorded while walking). Finally, a *track* refers to the entire movement dataset available for a particular moving entity.

Concerning the spatial scope of the involved contextual data, we follow Tomlin (1990), and refer to a *location* as the atomic unit of space with a distinct value assigned (a raster cell), a *neighborhood* as a sub-set of locations within a certain distance from a pre-defined location, in our case a position of a moving entity, a *zone* as a sub-set of locations located within a geographical area which is defined based on a separate zone layer (e.g. all temperature values within a certain land use), and finally a *layer* which spans the entire area of interest.

Table 1: Local, focal, zonal, and global equivalents on the levels of movement and spatio-temporal context data

Context operator	**Movement Data**	**Context Data – Spatial Dimension**	**Context Data – Temporal Dimension**
local	position	location	instant
focal	interval	neighborhood	time interval
zonal	trajectory	zone	era
global	track	layer	total time

Figure 1: Levels of analytical scope of movement and spatio-temporal context data



Concerning the temporal dimension of the context data, we distinguish between an *instant*, a set of values recorded at a certain fixed point in time (e.g. a temperature layer with values recorded at 2016-06-01 04:05:06), an *interval*, a time duration-based selection of *n* layers with attribute values around a certain point in time (e.g. the sub-set of temperature layers recorded maximal 2 hours before or after 2016-06-01 04:05:06), an *era*, a semantically defined selection of *n* layers with attribute values (e.g. the sub-set of temperature layers where the maximum temperature exceeded 16°C), and finally *total time*, which denotes the entirety of the available data for the full time span of interest (e.g. all available temperature layers).

Based on these definitions, any combination of context operators on the three levels unambiguously defines the spatio-temporal scope of the trajectory annotation process. Thus, an analysis of type *LocalFocalZonal* – we define the default order as movement data followed by context data (spatial dimension) followed by context data (temporal dimension) – treats each individual *position fix* of the movement track separately (*local*), and annotates them a value resulting from some combination of the underlying cell values within a certain *neighborhood* around their location (*focal*),

Figure 2: An exemplary trajectory annotation statement

Enriched Movement Data =

FocalAvg**Zonal**Min**Global**Max

OF *Movement Data* AT *Sliding Window* AND *Context Data* WITHIN *Zone*

however not just using the cell values of one but a selection of several layers recorded at different points in time (*zonal*).

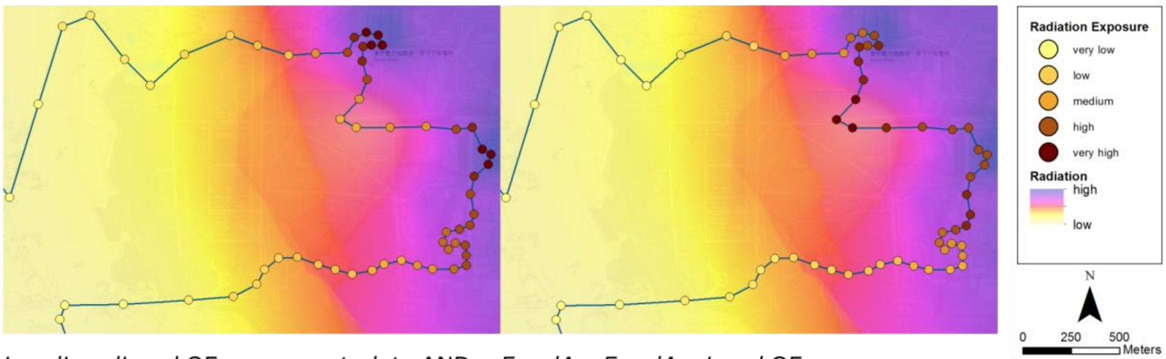
As a second step, for each level, the value processing function needs to be determined to describe how the input values, if more than just a single one, should be mathematically combined. In principle, in accordance with Tomlin's original concept, these can be any arithmetic, statistical or logical functions such as *average*, *sum*, *maximum* or *minimum*, *majority* or *minority*. Only in case of a *local* context operator, no such function is needed, since there is only one value.

With reference to traditional map algebra statements, figure 2 shows a formalized trajectory annotation statement in accordance with our concept. On the left side, the enriched movement dataset is set as the function's output. On the right side, the annotation function is defined with three slots to define the spatio-temporal scope of the movement data and the context datasets (shown in black), each of which is followed by a specific value processing function (shown in grey). Finally, connected by map algebra-typical modifiers such as *and*, *at* or *within*, the input datasets are set, and the function-specific neighborhood or zone definitions are determined, e.g. by defining a time interval for a sliding window, a distance threshold for a neighborhood, a zone layer for a zone, or a SQL query for an era.

4 Application

In this application example, we aim to assess a person's exposure to radiation per hour, e.g. a member of a disaster response team in the aftermath of a nuclear accident. For this, we created hypothetical test data, both with regards to the movement track and the underlying radiation data, which, together with the results of an implementation in Python, are shown in figure 3. As one can see, we tested two variants: in the first, we chose a simple *LocalLocalLocal* method, which is similar to the common approach of simple cell-to-point annotation as discussed earlier, but neither produces the intended radiation per hour, nor takes into account any positional inaccuracy of the track or temporal variation of the context data. Thus, by means of our proposed framework, we can also compute a more complex *FocalAvgFocalAvgLocal* method, which creates a sliding window on the level of movement data in order to receive the intended average radiation per hour. Due to potential positional inaccuracy, a spatial neighborhood of 25 meters is defined around each position fix and the average radiation value is calculated.

Figure 3: Exposure to Radiation per Hour



LocalLocalLocal OF *movement_data* AND *radiation_layer*

FocalAvgFocalAvgLocal OF *movement_data* AT *(1h)* AND *radiation_layer* AT *(25m)*

5 Discussion and Conclusion

This study proposed an analytical framework for semantically enriching movement trajectories with context data as well as a terminology for unambiguously defining the spatio-temporal scope of the analysis and the value processing method on each level. We expect our work to assist movement data analysts in selecting or developing a suitable annotation method based on the exact aim of the study as well as the characteristics of the available movement data, for instance with regards to the expected positional inaccuracy, and the context data, e.g. in terms of the spatial and temporal resolution. Our framework can be of particular value for more complex tasks, as sketched in the introduction, which require a more elaborated method than a simple cell-to-point annotation. At the same time, the proposed terminology can be useful to communicate the used methods.

Mainly due to the early stage of our research, however, there are still several limitations. Thus, we have not fully explored the potential ways to define focal or global spatio-temporal scope levels of the context data. Apart from a simple distance-based one, for instance, more complex neighborhood definitions involving e.g. a direction might be needed. Further, in case of multiple involved layers with multiple cells, different orders of calculation could be possible. Potential effects on the results need to be explored. Further, our framework is currently only applicable to cases where context data exists in the form of raster layers, and not to scenarios which require context to be modeled with discrete vector features.

For future work, we aim to address these shortcomings, and, on this basis, develop and implement a comprehensive toolset, which can then be tested in various scenarios.

References

Albrecht, J. (2007) *Key Concepts and Techniques in GIS*. Los Angeles, London, New Delhi, Singapore, Sage Publications.

Andrienko, G., Andrienko, N., Heurich, M. (2011) An Event-Based Conceptual Model for Context-Aware Movement Analysis. *IJGIS*, 25(9), pp. 1347-1370.

Andrienko, G., Andrienko, N., and Pelekis, N. (2008) Chapter 2 - Basic Concepts of Movement Data. In: *Mobility, Data Mining and Privacy*, Berlin, Heidelberg, Springer, pp. 1–26.

Block, B. A., et al. (2011) Tracking apex marine predator movements in a dynamic ocean, *Nature*, 475(7354), pp. 86–90.

Buchin, M., Dodge, S., Speckmann, B. (2012) Context-Aware Similarity of Trajectories. In: *GIScience 2012*, LNCS 7478, Berlin, Heidelberg, Springer, pp. 43-56.

Cagnacci, F., Focardi, S., Heurich, M., Stache, A., Hewison, A. J. M., Morellet, N., et al. (2011) Partial migration in roe deer: migratory and resident tactics are end points of a behavioural gradient determined by ecological factors. *Oikos*, 120, pp. 1790–802.

Demšar, U., Buchin, K., Cagnacci, F., Safi, K., Speckmann, B., Van de Weghe, N., Weiskopf, D., and Weibel, R. (2015) Analysis and Visualisation of Movement: An Interdisciplinary Review," *Mov. Ecol*., 3(1), pp. 2-24.

Laube, P. (2014) *Computational Movement Analysis*. Berlin, Heidelberg, Springer.

Laube, P., Dennis, T., Forer, P., and Walker, M. (2007) Movement Beyond the Snapshot - Dynamic Analysis of Geospatial Lifelines. *Computers, Environment and Urban Systems*, 31(5), pp. 481-501.

Shamoun-Baranes, J., Van Loon, E. E., Purves, R., Speckmann, B., Weiskopf, D., and Camphuysen, C.J. (2012) Analysis and visualization of animal movement, *Biol. Lett.*, 8(1), pp.6-9.

Spaccapietra, S. and Parent, C. (2011) Adding Meaning to your Steps. In: *Proceedings of the 30th International Conference on Conceptual Modeling (ER 2011)*, LNCS 6998, Berlin, Heidelberg, Springer, pp. 13-31.

Tomlin, C. D. (1990) *Geographic Information Systems and Cartographic Modelling*. Englewood Cliffs, New Jersey, Prentice-Hall.