Analyzing Relative Motion within Groups of Trackable Moving Point Objects

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Abstract. The overall goal of the ongoing project is to develop methods for spatio-temporal analysis of relative motion within groups of moving point objects, e.g. GPS-tracked animals. Whereas recent efforts of dealing with dynamic phenomena within the GIScience community mainly concentrated on modeling and representation, this research project concentrates on the analytic task. The analysis is performed on a process level and does not use the traditional cartographic approach of comparing snapshots. The analysis concept called REMO (RElative MOtion) is based on the comparison of motion parameters of objects over time. Therefore the observation data is transformed into a 2.5-dimensional analysis matrix, featuring a time axis, an object axis and motion parameters. This matrix reveals basic searchable relative movement patterns. The current approach handles points in a pure featureless space. Case study data of GPS-observed animals and political entities in an ideological space are used for illustration purposes.

Keywords. Change, Spatio-Temporal Analysis, Motion, Moving Point Objects, Motion Patterns.

1 Introduction

The only constant in the contemporary world is change. Nothing is ever stable. Sciences investigate change to understand the underlying processes, to find universal rules. The collection of data, the descriptive part of scientific activities, is necessary to have the foundations on which deductive work is building up [2].

According to Frank change comes in two forms: change of the objects of interest (*life*) and change in the position or geometric form of these objects (*motion*). Motion, the topic of this paper, is a spatio-temporal phenomenon.

Space is crucial to investigate motion, because a change of position can only be noticed in relation to a reference, mostly a spatial coordinate system. *Time* is crucial too as it is intrinsically linked with causation. Causation implies precedence, lack of precedence rules out causation [2].

Geographic Information Systems (GIS) provide a wide range of analysis tools for spatial science. Their potential to deal with spatio-temporal phenomena such as change is not yet very elaborate. In the late eighties the topic of time entered the field of GIScience. Langran identified the need to describe spatial change over time and examined the design of temporal GIS [8]. Hornsby and Egenhofer [5] present an approach to represent and model geographic entities in time. Peuquet [11] gives a detailed overview on today's issues in space–time data representation and tries to explain, why the representation of both space and time in digital databases is still problematic.

Examples for analysis of change on a process level are sparse in literature. Openshaw et al. [10] and Imfeld [7] give two examples. Openshaw et al. present an approach for spatio-temporal data mining. The Space-Time-Attribute Analysis Machine (STAM) and Space-Time-Attribute Creature (STAC) try to find clusters and other patterns in space and/or time in long-term illness census data without prior knowledge. Imfeld presents methods termed the time plot family to analyze mobile objects in their environment. In his approach the movements of up to two individuals are investigated in an analysis space featuring two temporal axes.

The classical situation for motion is humans or animals moving in space. These phenomena can easily be modeled and handled as a series of observations of moving points, represented as tuples of t, x, y and z coordinates. Due to substantial advances in tracking technologies, such as GPS and mobile device technologies, an increase in spatio-temporal data about moving objects can be expected. In the field of animal telemetry GPS technology provides observation data of previously unseen qualities and quantities [6].

In the late seventies Bertin used the procedure of seriation to find behavioral patterns in animal observation data [1, 9]. Seriation is an experimental tool for ordering and classifying two-dimensional tables relating to sets of elements. The rows and columns of a matrix are permutated such that, starting from any specific element, the other elements most similar to it are closest in the sequence. In one example he found behavioral response of woodlouses to a light source by ordering motion parameters using paper file cards.

Observations of moving point objects are not only seen in wildlife sciences, but also in other domains like social sciences, geomarketing, transport GIS (TGIS) or even the political sciences. Haggett's famous people on the beach illustrate such a social phenomenon [3]. Also, in social sciences political entities such as communities can be plotted over time in abstract ideological spaces e.g. between the extremes left, right, conservative and progressive [4]. A telecommunication company might be interested in the spatio-temporal behavior of cellular phone users for public relations or network expansion planning. Radio-tracked taxicabs in a city are an example for TGIS [12]. All those phenomena can be reduced to the basic phenomena of moving points and then might be analyzed by similar spatio-temporal analysis methods.

The overall goal of the research presented in this paper is to find, quantify and visualize user-defined motion patterns in groups of moving point objects. The detailed aims are:

- To develop a flexible analysis concept for the integrated analysis of motion parameters of groups of moving point objects.
- To identify, characterize and categorize the basic types of relative motion within groups of moving point objects.
- To identify (sub–)groups according to equal or similar movements.
- To develop algorithms to recognize patterns in the data. Finding patterns over time means identifying (a) the concerned individuals and (b) their location and extent on the time axis.

2 Analysis Concept

The basic idea of the analysis concept presented here is to compare the motion parameters of different point objects over space and over time. Thus, the fundamental concept underlying the analysis concept can be called "relative motion", giving the analysis concept its name: REMO (*RElative MOtion*).

The concept is based on the combination of the two ideas of arranging the tracking data tuples and detecting discrete motion patterns.

- For large spatio–temporal data sets systematic arranging is a key concept to gain insight. The first key approach is to transform the tracking data into arrangement or a configuration that reveals motion patterns (section 2.1).
- Basing on this arrangement, a second important approach is to search discrete instances of change rather than trying to perceive the entire motion processes. Analyzing incidents of delimited change is easier than analyzing the processes themselves. Every complex motion behavior can be fractionalized to discrete behavioral

patterns, such as "sudden change in motion direction" or "many objects moving with equal speed" (section 2.2)

2.1 The REMO Analysis Matrix

Let *N* be a set of individual point objects moving around (Fig. 1a). The four tracks could represent the observations of four caribou cows carrying GPS-collars (O_1 to O_4). The motion of every object is recorded as a path of exact coordinate tuples with the structure t, X_t, Y_t, Z_t. The recordings of the positions of the point objects must be performed synchronously (t_1 to t_5). Thus, at every time step a set of motion parameters can be derived from the original tuples, taking into account at least two consecutive observations. The three basic motion parameters are *motion azimuth*, *speed* and *change of speed (∂-speed)*.

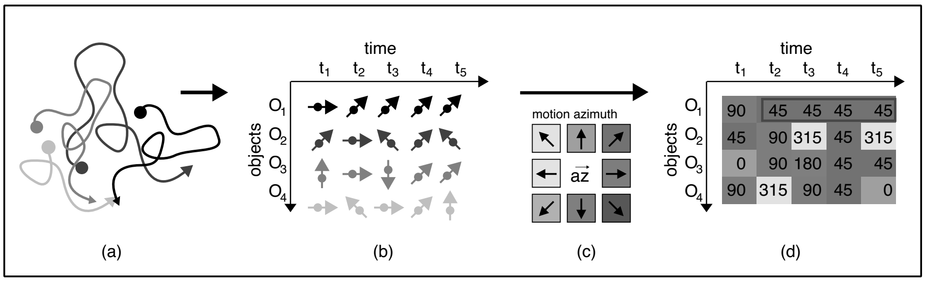

Fig. 1. The construction of the REMO analysis matrix

The motion parameter values are arranged in a matrix (e.g. motion-azimuth in Fig. 1b). Every row of the matrix represents the sequence of an object's motion parameter values in regular intervals over time. The rows with the object's motion parameter values are arranged so that coinciding observations are vertically aligned. Thus, the columns of the matrix represent time steps, specifying the object's temporally coinciding motion parameters. This matrix can be considered as a 2.5-dimensional analysis space: The horizontal axis is defined as the temporal axis (*time t)*, the vertical axis is defined as the *object axis* and the values represent the *motion parameter values*. While the temporal axis is ordered, the object axis includes no explicit order among the objects. The REMO analysis concept is constructed such that no a priori ordering among the objects is needed.

The REMO analysis concept compares the motion parameters of different point objects at different times. Therefore the motion parameters are grouped into discrete classes. For the azimuth eight classes have been chosen (N, NE, E, SE, S, SW, W, and NW, Fig. 1c). Also speed and ∂-speed have been reclassified: Eight classes of speed reduced to the unit interval 0 (slowest) to 1 (fastest) and eight classes of ∂-speed reduced to the unit interval -1 (maximum slowing-down) to +1 (maximum speeding-up).

In the REMO analysis concept space is continuous. In the strict sense the temporal dimension is discrete. However, since the temporal steps between the observations are kept short (in relation to the whole monitoring time frame) time shall also be considered as continuous. The temporal coverage of the motion is assumed to be complete. Missing observations might be interpolated.

The REMO matrix with the numerical description of the object's motion is the basis of all further analyses. A straightforward approach is to visualize the sequences of classified motion parameters in a halftone-coded matrix (Fig. 1d).

2.2 Basic Motion Patterns

The aim of arranging the motion parameters in a matrix is finding interrelations in the motion of a group of point objects. It is assumed that interrelations among the moving objects are manifested as patterns in the REMO matrix. Sequences and incidents that are somehow clustered on the time-axis and across the objects build a pattern in the REMO matrix. A pattern found in the REMO matrix could stand for a causal relation among the objects movements and initiates further investigation in the semantics of the observations.

What is meant by the term *pattern* in the REMO analysis concept? A pattern is a search template (e.g. a sequence of four times a motion azimuth of 45° found in the top row in Fig. 1d). A pattern is a defined set of motion parameter values with an extent in time and/or across the objects. Thus, patterns can span over the following two *dimensions* or their combination (Fig. 2).

- *(C) Patterns over time* (several times, one object (t:1); parallel to t-axis): Comparing the motion parameter values of one object at several times. Patterns may be cyclical or intermittent changes or trends in motion parameter values. Example: An object moves for four temporal intervals in the same direction.
- *(B) Patterns across objects* (same time, several objects (1:n); perpendicular to t-axis): Comparing the motion parameter values of the considered objects at a certain time. A pattern across objects is found, when a set of objects perform the same motion at the same time. Example: Five objects are moving in the same direction at time t.
- *(C) Combined patterns over time and across objects* (several times, several objects (t:n), both dimensions): The consideration of interrelation not only in one, but in both dimensions of the matrix discovers complex interactions between the motion

of many objects at several time steps. Example: Object O_x anticipates the motion direction of four other objects.

Patterns within one dimension are called *simple* (A, B), those over time and across objects are called *complex* (C). A pattern has a temporal extent called the *pattern duration* with a start–time, duration, and an end–time. At the object axis the range can vary from only one to all objects concerned. The number of involved objects is called the *pattern width*.

Patterns can be discontinuous. *Gaps* in the patterns are of thematic interest and thus explicitly allowed. In the temporal dimension a gap in a pattern is needed to describe *time lags* between e.g. the cause and the effect of a phenomenon. Gaps in the object dimension arise out of the unordered construction of the matrix.

Two objects performing e.g. the same abrupt change in motion direction may in real world space be positioned right next to each other or separated by a long distance. They are performing the same motion but in two different spatial contexts. Thus, the motion pattern is not the same and must be distinguished. The REMO analysis can be performed in two ways:

- *Motion Patterns without Neighborhood Information.* All objects are treated equally, no matter where they are in space, no matter whether they are close neighbors or have any other spatial interaction. Thus, in all these approaches the spatial dimension is reduced to the points' current motion parameters. The ordering dimension is time.
- *Motion Patterns using Neighborhood Information.* The absolute and relative positions of the moving objects are taken into account. This may happen as a preselection, based on proximity or other spatial interrelation.

Motion Patterns without Neighborhood Information. This section introduces a selection of the basic relative motion patterns in the REMO analysis concept (Fig. 2). The following analysis tasks are performed from a non-spatial perspective, all objects in the sample are taken into consideration, and the spatial relations among the objects are excluded. Thus, neighborhood does not matter.

Patterns over Time. Analysis over time searches for motion patterns parallel to the t-axis. These patterns are called SEQUENCE. To build a pattern over time, a minimum of two consecutive observations of one object is needed. Thus, the time frame lies between an interval of at least two consecutive observations and the extreme of the integrated analysis of all observations.

- The simplest and most obvious pattern is *constance*. The task is to find intervals with constant motion parameter values in an object's history (see grey box in Fig. 1d).

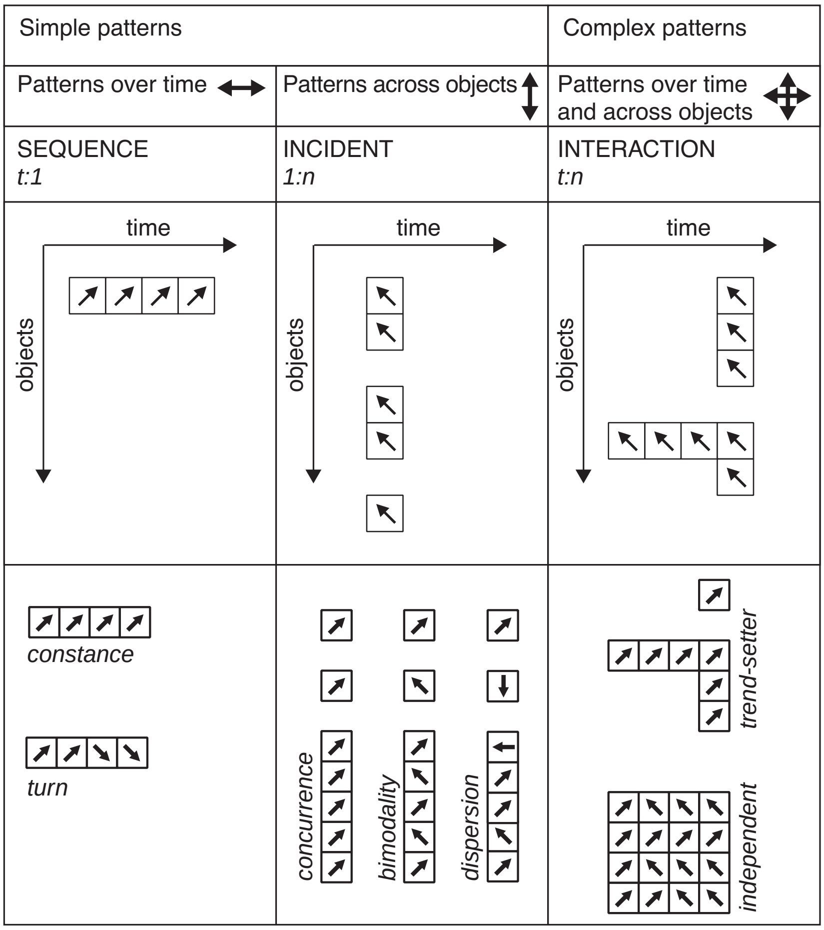

Fig. 2. Basic types of relative motion patterns

- A second sequence pattern is *turn*. A turn is a defined change in an object's motion parameter. An obvious turn is the alternation of the motion direction. Turns have (a) a parameter extent (value range) and (b) a temporal extent (duration).

Patterns across Objects. Analysis across objects compares the motion parameter values of a set of objects at certain moments in time. The task is finding INCIDENTS. In the REMO analysis concept an incident is a pattern in the motion parameter values of a set of moving objects that delimits this moment from the rest of the observation.

- *Concurrence* is the basic concept of patterns across objects, similar to constance in patterns over time. A concurrence pattern is found, when a set of objects, e.g. 60%

of the whole sample, show a synchronous or at least similar motion parameter values at a certain time.

- The pattern *opposition* describes a bi- or multipolar arrangement of motion parameter values. A typical case of opposition is the spatial splitting of a group of moving objects shown in a sudden appearance of two opposite motion directions (*bimodality*).
- The opposite of concurrence is *dispersion*. Dispersion can be an evident pattern in a group of moving point objects that is performing a non uniform or random motion.

Complex Patterns over Time and across Objects. The motion patterns of the previous sections are simple and extend either along or perpendicular to the time axis. The patterns in this section combine motion patterns along and perpendicularly to the time axis of the REMO matrix, trying to find INTERACTIONS between the sequences of one object and incidents among the others.

- The most obvious complex analysis task is seeking for *trendsetters*. The basic idea is to find objects that anticipate a certain pattern of motion parameters, that is afterwards reproduced by a set of the other objects. Thus, the complex pattern trendsetter is a combination of the simple patterns concurrence and constance.
- A pattern similar to the trendsetter can be called the *independent*: This pattern can be found if an individual moving point object goes his own way, ignoring the movement of the other objects of the sample.
- Another complex pattern is *propagation*. One objects starts to show a certain motion parameter value, and little by little other objects take part. With every time step more objects are involved.

The simple concept of concurrence can easily be extended along the time axis. The search template is simply extended to a temporal interval, in which a set of objects shows the same or at least similar motion parameter values. There are two basic patterns belonging to this complex pattern category.

- The first, *group turn* is a sudden change in the motion parameter values of a whole group of moving objects.
- The second is *group concurrence*. For this pattern a defined group of moving point objects shows a synchronous motion over a certain temporal interval, showing heterogeneous motion before and after.

Motion Patterns Using Neighborhood Information. Assuming that the objects of a group perform their motion in relation to the movement of other group members, the motions of the point objects must also be analyzed in their spatial context. The convergence of many caribou cows to the calving site, for example, can not be seen only in the parameters motion azimuth, speed and ∂-speed. To recognize this process also the motion of the objects in absolute space must be considered. The question is: Do objects that are showing a relative motion pattern have any spatial interrelation?

A variety of measures can describe the location of an individual relative to the others. They can be summarized as CENTRALITY/PERIPHERY MEASURES.

- The archetype of this kind of patterns can be called *flock*. A flock is a point cluster showing concurrence, i.e. show a conform motion. Measures need to be defined or adapted that indicate the presence of clusters in the REMO matrix. This opens a connection to the broad field of cluster analysis.
- The relation of *convergence* is found when a group of point objects is simultaneously heading for an identifiable point in space.
- The opposite relation *divergence* describes a group that disperses.

These patterns can only be detected by considering simultaneously the relative and absolute motions of objects in space and time.

The concept of the trendsetter excludes deliberately the relative position of the objects to each other in real space. In consideration of spatial interaction, the pattern trendsetter can be broken down further into the patterns *geese flock* and *guru*.

- In the case of *geese flock* the trendsetter shows a spatial proximity to its followers.
- The *guru* shows its trend-setting movement spatially apart from its followers.

3 Test Data Sets

The ultimate purpose of this research is the development of tools that allow quantitative analysis, not visualization that leads to qualitative analysis. Even though visualization is not the prime research objective, it is a powerful development approach. Thus, this conceptual paper illustrates the principles of the REMO analysis concept using visualizations of real data. The motion parameters azimuth, speed and ∂-speed of two test data sets are plotted in a black and white halftone-coded matrix (see online version for color pictures).

3.1 The Porcupine Caribou Project

The Porcupine Caribou Herd Satellite Collar Project is a cooperative project that uses satellite radio collars to document seasonal range use and migration patterns of a Porcupine Caribou herd in northern Yukon, Alaska and NWT. At the start of this project, 10 cow caribou were captured in October and November 1997 and equipped with GPS collars. Since then the caribou were tracked in approximately weekly intervals. (Details about the Porcupine Caribou Project including the original tracking data can be found at http://www.taiga.net/satellite/index.html)

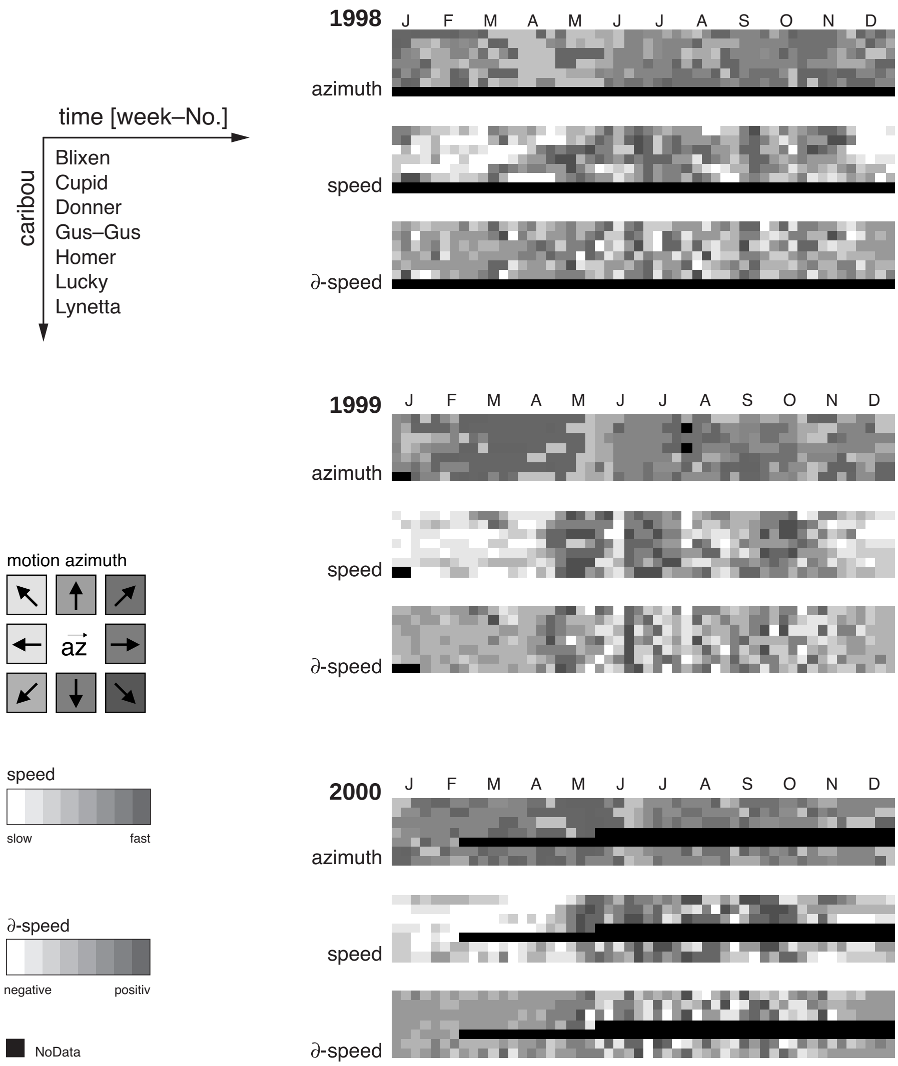

Fig. 3. REMO-Matrix of selected individuals of the Porcupine Caribou Project

Looking at the halftone–coded matrix an annual migration structure can be seen (Fig. 3). During the spring months March to May the N– and NE–heading azimuths dominate (light-grey). In the second half of the years rather the S– and E–Azimuths appear to prevail (dark-grey). While the winter and spring months show mainly constant slow movements, summer and fall see a more complex pattern of slow and fast movements, speeding-up and slowing-down, respectively.
Going into detail, the plot pinpoints some basic relative motion patterns. A phase of highly synchronous movements in June and July 1999 strikes as an obvious feature. This phase includes several *concurrence* patterns in the azimuth plot with pattern widths of up to 5 of 7 individuals. *Constance* patterns are pretty common in all plots, especially in the springtime. In June and July 1999 a *group turn* pattern from NW to SE is very obvious.

3.2 Swiss Political Districts Moving in an Abstract, Ideological Space

The frequently held popular referendums in Switzerland allow to make detailed inferences about value–conflicts within the society. Hermann and Leuthold [4] developed an inductive approach to discover the basic ideological conflicts in Switzerland. Performing factor analysis on referendum data at the district level of all 158 federal referendums held between 1981 and 1999, they discovered a structure of mentality, which is composed of three dimensions: left vs. right, liberal vs. conservative and ecological vs. technocratic. The projections of this multidimensional ideological space, taken in pairs, provide a total of three two–dimensional maps of the political landscape of Switzerland.
In these two–dimensional ideological spaces the 185 districts can be localized in intervals of one year, from 1981 until 1999. Irrespective of their political and social meaning, the districts can be considered as moving points in a two–dimensional space. Thus, this is a data set that is suited for the REMO analysis concept.
(An animated view of the Swiss districts moving in the ideological space can be seen under the URL: http://www.geo.unizh.ch/gia/research/sotomo/gifs/filmCH.gif).
All districts of a canton are grouped together in the matrix (Fig. 4). Thus, proximity in the matrix corresponds to a certain institutional and cultural similarity.
The first overview allows an obvious distinction between the German speaking (topmost two fifths of districts) and the French and Italian speaking, latin part (lowermost two fifth of districts) of Switzerland. Whereas the german speaking part in general moves to the right, the latin part moves to the opposite left pole (azimuth). The French and German speaking, bilingual Canton of Fribourg (FR) endorses this general impression. Regardless of its separation from the other latin Cantons by lower district numbers, it shows a latin style color pattern.

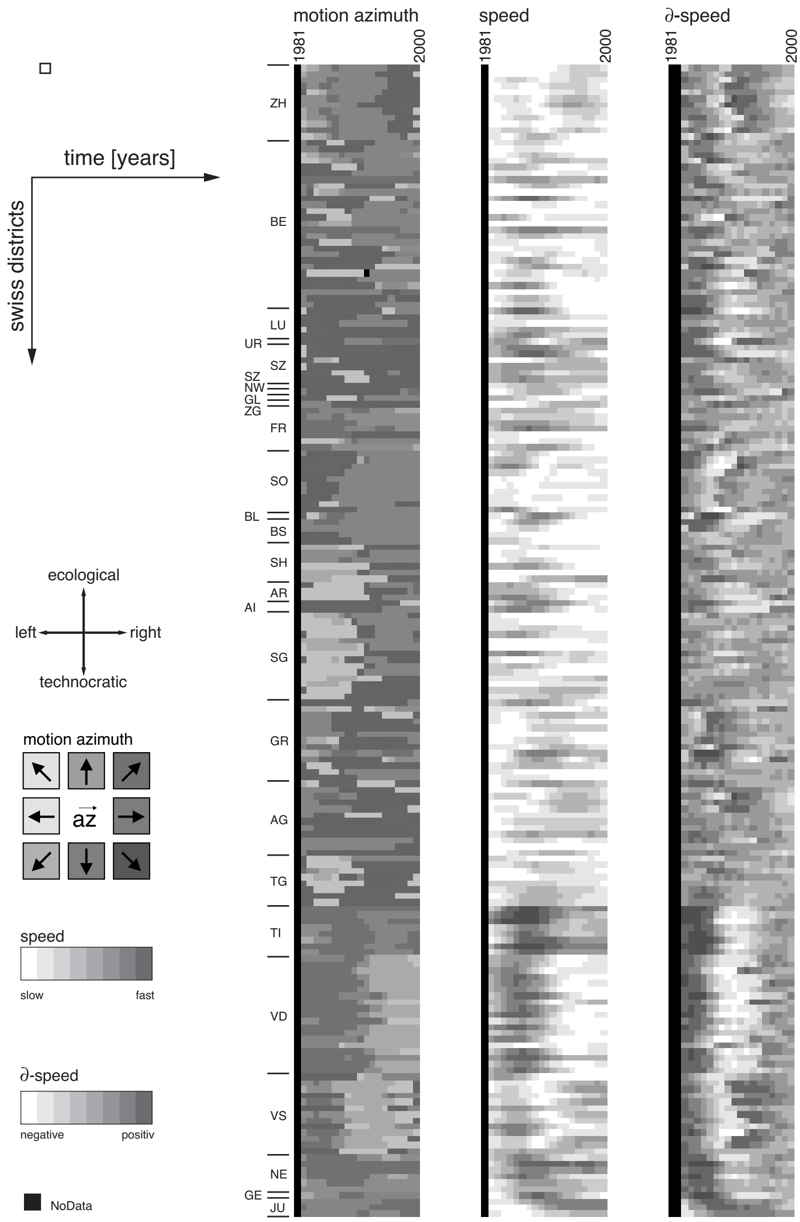

Fig. 4. REMO-Matrix of the swiss political districts moving in an ideological space

By the means of the lexically ordered districts, the *concurrency* sequence of many cantons is apparent. Obvious examples are the cantons Ticino (TI), Vaud (VD) and

Zurich (ZH) showing very comparable patterns through all districts and trough all three plots.Seeking for other basic REMO patterns *constance* strikes the most. In the azimuth plot many districts show persistence in their motion azimuth class for up to ten and more time steps. Also *turn* patterns are often seen. The canton of Zurich (ZH) shows some very obvious examples in the period 1985 to 1989. Most of its districts perform a directional turn from "left–technocratic" over "technocratic" to "right" in only four time steps, i.e. four years respectively. The initial starting point for the sequence may vary up to three years, but the overall azimuth change pattern remains the same. Another basic pattern can be seen in the districts of the Canton of Zurich. The district of Meilen (No. 7 from the top) anticipates the azimuth change of almost all other districts: Already in the early nineties it performs the directional change from "right" to "right–ecological". The rest of the districts follow after 1992 one by one.

4 Discussion

The integrated investigation of the motion parameters motion azimuth, speed and ∂-speed provided new insights in the large and complex data sets. The possibility to be simultaneously aware of different motion parameters over any desired time frame allows a new way of investigating processes within groups of moving points.
The REMO analysis concept allows the identification of (sub–)groups showing equal or similar motion parameter values. Group identification was moderately possible within only a dozen individuals in the porcupine caribou data and explicitly possible in the "moving Swiss districts" data.
The two prototypical examples of the porcupine caribou data and the Swiss political districts data show that visualization is a powerful tool for the REMO analysis concept and thus must be implemented in an integrated analysis framework. But these examples also reveal the limits of analysis based exclusively on the halftone–coded matrix visualization. The larger the data sets are, the more difficult it is to interpret the visualization of the halftone–coded matrix. For larger data sets it is essential to develop precise measures and selective tools to identify events, processes and relationships in a quantitative and reproducible manner. The analysis of concurrence in the objects can e.g. be performed considering the whole time frame and all objects. Therefore, a measure of concurrence is used. This measure indicates numerically how much the motion parameter values of one object correspond to the motion parameter values of all the other objects. This measure is computed for every object every time step and accumulated over the objects. Plotted in a *cross-classified table of the accumulated concurrence* (cumulative concurrence of object A to all others, B to all oth-

ers...) measures may give a condensed insight in the dynamics in the motion of the group.
Even though the Porcupine Caribou data set (Fig. 3) has almost the optimal data structure required for the REMO analysis concept, it has some structural shortcomings and thus illustrates some methodological challenges for the REMO analysis concept. First of all, the individuals are not localized absolutely synchronously. Even though the observation week numbers correspond, the exact day of observation may vary up to several days. Furthermore, the tracking interval varies irregularly over the duration of observation project from twice a week over weekly to every second week. As a straightforward approach to preprocessing, the REMO analysis concept works with a linear interpolation of the observation fixes in weekly intervals along the time axis. Last but not least some caribou died during the observation period (Gus-gus and Homer) and were replaced by other collared animals (Lynetta).
In the seriation procedure [9] the knowledge discovery in the analysis process happens by human cognition after reordering rows and columns in a matrix. In contrast, the REMO concept is designed to find patterns automatically and numerically without reordering the objects in the matrix. The STAM/STAC data mining approach [10] is made for localizing clusters in spatio-temporal point data, in basically immobile observation points of disease cases. In contrast, the REMO concept is designed for tracking data describing moving points. Whereas the time plot family [7] is designed to analyze the motion of one or at most two individuals, the REMO concept is designed for an unlimited number of objects.

5 Conclusions and Outlook

This paper presents an analysis concept for spatio-temporal observation data, called the REMO analysis concept. The REMO concept allows analyzing the relative motion of many moving point objects. The concept bases on the combination of two key ideas. First, several parameters describing the individuals motion are arranged in an analysis matrix. The rows of the matrix represent the individuals, the columns consecutive time steps. Second, spatio–temporal "behavior" and interrelations within groups of moving point objects are manifested as patterns in the REMO matrix. Basic patterns of relative motion such as *constance*, *concurrence* or *group turn* can in fact be identified and localized in space–time. The testing of the REMO analysis concept both on typical GPS–tracking data and abstract socio–political data, showed its universally applicable layout. The REMO analysis concept helps to discover interrelations in any kind of observation data of moving points objects, no matter whether the

data describe moving animals, moving people or any kind of moving entity in artificial spaces.
The next steps of this ongoing research project include the advancement of a prototype environment to test and enhance the REMO analysis concept. The goal of this prototype is the implementation of measures and algorithms to describe and identify the patterns in a quantitative way. Therefore, we will define a pattern definition language. In the testing phase we will test the REMO analysis concept with constructed artificial and additional real observation data sets. Furthermore we will investigate the influence of different motion parameter classifications on the pattern detection results. Last but not least we will extend the system to extract arbitrary pattern inherent to the data.

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