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TEAMwISE: Synchronised Immersive Environments for Exploration and Analysis of Movement Data

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Figure 1: TEAMwISE on a tiled display wall, showing several synchronised view perspectives on a flock of storks: Overview (lower right), focus bird (upper right), and use of thermals in the flock, with altitude analysis charts and data windows (left).

ABSTRACT

The recent availability of affordable and lightweight tracking sensors allows researchers to collect large and complex movement datasets. These datasets require applications that are capable of handling them whilst providing an environment that enables the analyst(s) to focus on the task of analysing the movement in the context of the geographic environment it occurred in. We present a framework for collaborative analysis of geospatial-temporal movement data with a use-case in collective behavior analysis. It supports the concurrent usage of several program instances, allowing to have different perspectives on the same data in collocated or remote setups. The implementation can be deployed in a variety of immersive environments, e.g. on a tiled display wall or mobile VR devices.

CCS CONCEPTS

• **Human-centered computing → Collaborative and social computing systems and tools**; **Visualization systems and tools**.

KEYWORDS

immersive analytics, immersive environments, animal movement

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1 INTRODUCTION

The analysis and visualisation of large movement datasets, as well as the development of corresponding concepts and methods, is a challenge that is tackled in an interdisciplinary research area that involves biologists as well as computer scientists. There has been substantial progress in the development of corresponding analysis and visualisation methods and solutions in recent years, e.g. regarding the classification and visualisation of trajectories, or the classification of behavior, see [10] for a review. Many of those solutions have a particular focus on (visual) analytics, statistics or computational tasks, rather than on an unbiased explorative approach. Thus, there is a need to further integrate visual, analytical and user-centered methods in a methodological framework [1, 23]. Some promising methods in this direction have been proposed, e. g. event-based analytics [1] or analysis by enrichment [33].

We present TEAMwISE (**T**ool for **E**xploration and **A**nalysis of **M**ovement data **w**ithin **I**mmersive **S**ynchronised **E**nvironments) – a framework for the exploration of movement data across devices in an immersive fashion. TEAMwISE supports collaborative data analysis, either collocated in an immersive or semi-immersive environment, like a tiled display wall (TDW), or via shared mobile virtual environments. It combines a visualisation of trajectories in the geographic context with movement analysis, and supports the synchronised interactive visualisation of multiple views.

Our framework has been developed in close collaboration with researchers from the Max-Planck-Institute for Ornithology and the Department of Collective Behaviour at the University of Konstanz, who provided valuable insight into their research and feedback on our designs and implementation prototypes.

1.1 Research Questions

The biologists analyse animal behavior by tagging animals in the wild using sensors that collect data on the movement and environmental and physiological parameters over a longer period of time. Often, GPS sensors are used that provide a good estimate of the movement over time. The data under analysis is usually a combination of directly measured data, which is coming from sensors that the birds are tagged with, known data, as for example bird age and species, derived data, such as environmental conditions like wind speed calculated from dead reckoning [37], and additional data obtained from other sources, e.g. large scale weather conditions.

Research questions that the biologists try to answer include

- What are behavioural patterns of individual animals and animal groups?
- What are the main influence factors that animals base their decisions on?
- How can behaviour and its influencing factors be derived from movement data?
- How do animals communicate and interact with other animals and the environment?
- Are there specific roles for animals in a group, and how are they assigned and distributed?
- What are specific or recurring events during the lifetime or a specific timespan of an animal, e.g. reproduction or feeding, and how can they be classified?

Several research questions for computer scientists naturally arise when methods, approaches, and environments have to be developed that support the domain experts in answering these questions:

- How can abstract/spatial data, and 2D/3D representations be combined to clearly depict the environment, allowing intuitive interpretation of analysis results in this context?
- What are natural human-computer interaction patterns for biologists in immersive environments?
- What are the requirements for efficient algorithms and environment design for human-centered / human in the loop immersive analytics?
- What are suitable methodologies for collaborative immersive data analytics of animal movement data?
- How can the proposed methodologies and environments be evaluated for their efficiency in practice?

1.2 Related Work

Movement analysis and in particular the analysis and visualisation of trajectory data [5, 22, 25, 34, 36] has been a research topic for a long time in a variety of contexts, including algorithmic treatment [40] as well as applications [4, 18]. A particular focus has been on the development and implementation of respective methods in the field of visual analytics, see [4, 16, 33] or for reviews [1, 3, 10].

Methods developed for the visual representation of spatio-temporal data are often either abstracting data to highlight certain characteristics, or only use two of the three axes in 3D-visualisations for spatial dimensions. The space-time cube (STC) [15] uses two axes for spatial dimensions and the third for the temporal dimension [13, 25]. The visual expressiveness of the STC is limited and its applicability is heavily depending on the data domain and the research task [10, 17, 21]. But in case of 3D spatial datasets, the visualisation in three spatial dimensions can enable a more precise analysis of spatial relationships and increase the degree of reality, in particular using stereoscopic 3D (S3D) technologies [14, 26, 32].

In movement ecology, abstraction or aggregation might not always yield an appropriate result since the observed individuals are then implicitly assumed to be homogeneous. Thus, a main challenge is to provide an environment that enables exploration of individual behaviour within a broader dataset, preserving the semantic context of the data. This covers the fact that the object of investigation is a living being, whose decisions and observed movement may have been influenced by its environment (we refer to this as *semantic preservation*). Some existing approaches try to explicitly address this [21, 31, 34, 35]. One aspect of semantic preservation is the animation of the data, as it reflects movement. This has been incorporated into an application by Andrienko et al. [6], and the importance has been highlighted by Kjellin et al. [17]. To ensure semantic preservation, it is required to integrate the environmental context into the visualisation, e.g. by satellite maps or terrain models. Several approaches to incorporate satellite maps have been proposed, see e. g. [2, 19, 22, 25, 31]. McEachren and Kraak [23] also state the need for more integration of the reality in the visual approaches as a challenge in geovisualisation. Yang et al. investigated the use of maps and globes in VR [38]. While some work on the calculation of derived data exists, in particular for wind estimation [37], it adds further uncertainty that needs to be taken into account.

The principles of giving the user control over the time and the opportunity to see the data from different perspectives has been investigated by Andrienko et al. [6]. Additionally, Li et al. [22] developed an algorithm that computes interesting viewpoints for further analysis. But their visualisation again focuses on the aggregation of the underlying data. Aigner et al. [1] partially adapt a temporal classification of Frank [12], which includes the distinction of ordered time domains and domains with multiple perspectives. They mention that most of the available applications for the visualisation of time-oriented data focus on ordered time domains. In [23], McEachren and Kraak accordingly state the need of applications that support dynamically linked views.

Zhang et al. [39] investigated the possibilities of bringing the visual exploration of geo-spatial data into immersive environments by using a spherical visualisation in VR. However, they did not incorporate methods for time control or animation. The recently emerging field of immersive analytics [11] investigates how immersive environments can best support analysts in their tasks by maximising mental involvement and hence efficiency, in particular in collaborative work scenarios. An early prototype of our framework was used in a comparison study of the potential of different immersive environments for collective behavior analysis [28]. Lee et al. proposed an approach for spatio-temporal data exploration [21] by allowing the analyst to control the projected image via hand gestures. Arsenault et al. [7] presented a system that allows the user to navigate through space and time in spatio-temporal data, including animation, but their system is designed to be used on a desktop computer as single user.

2 GOALS AND CONCEPT

Several goals for TEAMwISE naturally arise from the research questions stated in Section 1.1. A main goal is to provide a framework that enables analysts to observe the same movement situation from multiple perspectives, both in a single-user and collaborative setting. In discussions with our expert collaborators, we concluded that different perspectives on the same animal, and similar or differing perspectives on multiple animals, can provide not only overview and detail of movement, but support the analysis of interaction between animals and between animals and environment. The perspectives may vary in the viewpoint (e. g. a static view of a bird flock and views of an individual, see Fig. 1) or in the point in time (with a temporal gap between perspectives). Additionally, we want to present relevant aspects of the movement context (e.g. environmental information) and support collaborative analysis, which is often an important part of the analysis workflow.

To allow the researchers to easily access their existing data, we implemented an interface to the Movebank, an online animal movement repository [24]. To achieve this, we use OpenCPU [30] to create an R interface for TEAMwISE which then makes use of the move package [20] to access the Movebank. We use one webserver to host the content and another websocket server to manage the synchronisation features, both running in the Node.js runtime [29]. The browser-based visualisation and the basic interactions are using Cesium, a javascript library for geographical globe and map visualisations [8]. For abstract data visualisation, we use D3 [9].

In order to allow easy access on a multitude of device types, we use a web-based solution that can be easily accessed via a web-browser.

The main pillars of our framework are the visual representation, the synchronisation between program instances (across devices), and the underlying analytics.

2.1 Visual Representation

Users can view and analyse the movement in the environmental context in which it happened, either as static trajectories or as an animation. We focus on semantic preservation by providing a visualisation that includes relevant features of the real-world environment. Time is represented as a continuous stream, and the three-dimensional visualisation space can be used for the spatial visualisation. Especially for the investigation of bird movement data, incorporating the altitude in addition to longitude and latitude may be crucial. We visualise the movement trajectory as a user-adjustable 3D polyline with additional data mappings on visual cues such as color. The visualised context information includes satellite imagery and terrain information, which covers geographic context as well as vegetation, land use, and features that might be used for navigation or movement by animals, e.g. rivers and roads.

The user can freely move around the virtual camera (viewpoint) in the environment, attach its position to an individual, or select a fixed perspective on an individual or a group. The system also provides several pre-defined perspectives for ease of use. The time itself is represented as a timeline at the bottom of a view, with a moveable slider handle showing the current point in time. The analyst can choose to animate the data with a customizable velocity, or just explore different timepoints by freely moving the handle to any point in time. The analyst is also able to parameterise the time span for which the trajectory of an individual is represented in the visualisation. Results from the automated analysis can be mapped to visual variables like color, size, shapes etc. In case the data is available from drone or plane flights, the visualisation can be further enriched with point clouds, e.g. to incorporate vegetation structure.

2.2 Web-based Synchronisation

Our framework facilitates collaboration by supporting synchronized instances and shared immersive environments. Having started a TEAMwISE session, one can start several program instances - independent of whether they are started on the same or multiple devices. All instances that participate in the same session are synchronised through a central server. There are two roles of instances: masters and slaves. While any change in one of the synchronised features in a master instance will directly be propagated to any other registered instance, the slaves are not able to change features. Synchronisation includes several dimensions that can be configured by the analyst. As a base case, one can synchronise the current point in time of the animation and the dataset under investigation. Additionally, one may also decide to synchronise the camera position (in order to show interesting perspectives to others) or the marking or annotation of individuals.

Distributed collaboration is possible, e.g. by starting slave views for remote master views, allowing to mutually discuss interpretation of the data. For a single analyst, multi-screen and multi-perspective arrangements with different view- and time-points can be customized depending on the user's task, preferences, and data

Figure 2: Stork Sierit returning from winter migration. The destination, Lake Constance, is not visible from her current position due to a mountain range.

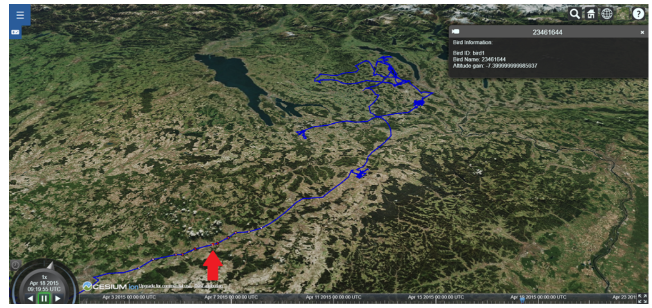

Figure 3: Last part of *Sierits* route (blue line), the arrow shows its position at the same timepoint as in Figure 2.

set specifics. This enables the same analyst to view the animation from several perspectives, i.e. through different virtual cameras. Collocated collaborative analysis is easily possible on large display walls and immersive multi-screen environments, see Fig. 1. Multiple screens can, e.g., be designated for a common master view, with multiple additional personal master or slave views on further screens, such that multiple researchers can observe different animals or different perspectives in a time-synchronised fashion. Through the web-based architecture, there are several environments from which one can join a session: a TDW, a regular desktop setup, a smartphone or tablet (natural touch interaction is supported), or in mobile VR via a smartphone in a cardboard.

In addition, multiple servers can be started concurrently, allowing for completely independent instances, e.g. to have a 'private' unsynchronised view in a collaborative setting.

2.3 Analysis

The framework has several basic analysis methods and corresponding visualisations, e.g. on entities' distances, altitude changes and profiles. These can be complemented by extensions. The modular structure of our framework allows to integrate different algorithms via an extension mechanism, and to have the user parameterise and run them from the GUI. The resulting information is stored so that it can be mapped into the visualisation or be used for further analytics during the session. As there is a large number of methods available in R and python packages, which the biologists are also partially familiar with, we decided to provide an interface to R and python. Several example analyses such as leader-follower classification [27] and nearest neighbor relations are already implemented.

3 APPLICATION CASE

To exemplify the system usage, we present a small part of a recent study that we worked on together with our biologist collaborators. In the study, we investigated how storks find their way back after winter migration. The underlying data reflects a homing flight of a one-year-old stork called *Sierit* back to Radolfzell, Germany (the end of the trajectory in Fig. 3 close to Lake Constance) in 2015. On its way back home, *Sierit* takes several wrong decisions, which analysts can easily spot in the visualisation. Their aim is to investigate the decision points to see why these mistakes probably happened, and how the overall navigation process actually works.

Here, we show a situation that arose quite at the end of the homing flight. *Sierit* was quite close to Lake Constance, but did not manage to directly head over and kept flying straight to the south. Moving to the point in time where this decision was taken, one can see that from its actual height the lake was not visible but hidden by a mountain range (Fig. 2). Lake Zürich however is visible in the south, leading to a misinterpretation and -navigation. TEAMwISE facilitates the analysis of such situations and to identify navigation patterns and landmarks, greatly supporting the biologists' workflow. Fig. 1 shows multiple perspectives on a tiled S3D Display wall. These perspectives can be distributed freely across the monitors, and switched between 2D and S3D mode. By using S3D, the user is able to better perceive the stork's movement direction within the flock towards the sky. The landscape below the storks is visible from several perspectives, supporting semantic preservation. Different perspectives also support the analysis of the field of view of individual storks, illustrating potential orientation towards leading or neighboring storks in the flock.

4 DISCUSSION AND OUTLOOK

We presented TEAMwISE, a web-based framework for movement analysis in immersive environments, and demonstrated its use in an application case. It can be easily extended by users to integrate further analysis methods. Our current developments include more natural interaction with the TDW environment, and the integration of more data sources, e.g. on land use and vegetation, in order to provide further information relevant for the analysis. We will also evaluate synchronisation concepts and representations for collaborative work. The data sets used by us for the use-case evaluations are available at Movebank [24].

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