Efficient Visual Analytics of Localized High-Frequency Multimodal All-Traffic Trajectory Data at Urban Intersections

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Abstract:

Trajectory data refers to the ordered sequences of spatio-temporal positions that describe the path of a moving object over time (Oueslati et al., 2023). Advances in location-acquisition technologies, particularly GNSS, have facilitated the collection of massive trajectory datasets (Zheng, 2015). Depending on the mounting location of the positioning sensors, trajectory data can be categorized as trajectory data generated by on-board, mixed, or off-board sensors.

<table>
<tr><th rowspan="2">Category</th><th rowspan="2">Sensor Mounting Location</th><th colspan="2">Data Coverage</th><th rowspan="2">Representative Sensor</th></tr>
<tr><th>Coverage of Objects</th><th>Coverage of Space</th></tr>
<tr><td>On-Board</td><td>Only on objects</td><td rowspan="2">Only objects with sensor mounted</td><td>Outdoor space of any size</td><td>GNSS</td></tr>
<tr><td>Mixed</td><td>Both on and outside objects</td><td rowspan="2">Only within sensor coverage</td><td>Bluetooth, RFID, Wi-Fi</td></tr>
<tr><td>Off-Board</td><td>Only outside objects</td><td>All objects within sensor coverage</td><td>Camera, LiDAR</td></tr>
</table>

Table 1. Classification of Trajectory Data Based on the Mounting Location of Sensor

Compared with the first two categories of trajectory data, which are directly collected by the sensors, the third category is indirectly generated through intermediate data, such as optical images and point clouds. Due to advancements in computer vision technology, the generation of off-board trajectory data has become efficient and accurate (Guan et al., 2024). Moreover, the trajectories of all objects within the sensor's range can be captured with a high frequency.

Urban intersection is a common scenario for the generation of off-board trajectory data. Using off-board roadside sensors, such as cameras and LiDAR sensors, all traffic objects of different mobility modes within the range can be intensively captured and tracked. Therefore, the localized trajectory data of those traffic objects is generated with a high temporal frequency. Based on the characteristics of the data, especially compared with on-board and mixed trajectory data, which can only cover the traffic objects with sensors mounted and sample a small portion of all traffic objects, the data can be termed as **localized high-frequency multimodal all-traffic trajectory data**. It opens up many opportunities for data-driven studies of road user behavior and traffic psychology and the interaction and dynamics between different road users.

Off-board trajectory data accumulates rapidly over time at observed urban intersections, resulting in massive and complex datasets. Such massiveness and complexity make it scientifically valuable for uncovering deep-seated insights but also pose what can be described as the 3H challenges:

1. **High Spatio-Temporal Density**: The data is characterized by very high spatial and temporal density due to the full coverage of all the traffic objects within the range with a high sampling frequency.
2. **High Interactivity among Objects and between Objects and the Environment**: The data records the frequent and intricate interaction, not only among traffic objects, such as yielding or overtaking, but between objects and the environment, such as pulling into a roadside parking space or stopping for the traffic light to turn green. Therefore, the data is inherently interconnected rather than isolated or fragmented.
3. **High Dynamics Represented by Variable Motion Patterns and Random Keyframes**: The intensive interactions between traffic objects result in highly dynamic behaviors, including rapid and frequent changes

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in position, speed, direction, and acceleration. These dynamics lead to variable motion patterns, where keyframes, such as moments of starting, braking, or accelerating, occur unpredictably.

Visual analytics can significantly contribute to meeting these challenges as an efficient tool for analytical reasoning through interactive visual interfaces (Thomas & Cook, 2005). This study will introduce a prototypical visual analytics system tailored to localized high-frequency multimodal all-traffic trajectory data. It addresses the challenges and aims to facilitate the exploration of traffic dynamics at urban intersections. The following analytical strategies are proposed:

1. **Semantic Modeling of Urban Intersections**: Modeling urban intersections based on streetscape elements, such as vehicle lanes, bicycle lanes, sidewalks, crosswalks, parking spaces, etc., to provide semantically meaningful contexts of traffic objects that go beyond mere spatial coordinates.

2. **Semantic and Attribute-Based Filtering**: Data filtering using both existing labels (e.g., timestamp, category, ID) and enriched semantic labels derived from semantic modeling to facilitate precise and targeted analysis.

3. **Keyframe Identification**: Detecting critical timestamps in the dynamic movements of traffic objects, such as moments of acceleration, deceleration, turning, and entering or exiting key interaction areas (e.g., crosswalks), to highlight significant behavioral events.

4. **Effective Clustering for Pattern Discovery**: Grouping traffic objects based on the identified keyframes and other parameters to facilitate the discovery and generalization of hidden movement patterns of traffic objects in each category.

5. **Interaction Analysis in Multiple Dimensions (Kinematics, Behavior/Intension, Safety)**: Analyzing interactions among traffic objects and between objects and the environment through multidimensional metrics to reveal complex dynamics, such as distance, direction, speed, acceleration in kinematic dimension, yielding, overtaking, crossing, avoiding in behavior/intention dimension, and risk levels in safety dimension.

6. **Perspective Switching for Tailored Insights**: Enabling users to toggle between various perspectives, such as an overview or specific views focusing on vehicles, pedestrians, cyclists, or their interactions, thus ensuring a flexible and comprehensive analysis experience.

The system demonstrates a case study with data collected by a roadside LiDAR station at an urban intersection in the Maxvorstadt, district of Munich, Germany. The dataset was collected at peak times over two days, totaling more than 5 hours at a frequency of 10 Hz. Trajectories of all traffic objects are recorded as 3D bounding boxes with timestamps and IDs, and each bounding box is described by nine parameters, including the 3D coordinates of the centroid, the 3D size of the box, and three rotation angles.

By providing an interactive and dynamic visual analytics platform for localized high-frequency multimodal all-traffic trajectory data at urban intersections, the system aims to assist in identifying bottlenecks, optimizing traffic flow, and improving safety at urban intersections. For instance, it can highlight near-crash events, analyze pedestrian-vehicle interactions, and evaluate the effectiveness of traffic interventions such as new lane configurations or signal timings. Furthermore, the system will provide opportunities to advance research in traffic behavior and urban design by uncovering nuanced movement patterns and interactions among different road users.

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