Multidimensional dynamic visualization of stock limit order books

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Abstract

This work presents an interactive visualization tool designed for the analysis of high-frequency *Limit Order Book* (LOB) data. The tool enables users to explore large volumes of market data, identify potential anomalies, and gain insights into market behavior. By integrating a time-series price chart with a heatmap matrix for multi-dimensional analysis, the system allows for detailed inspection of order flow dynamics across multiple instruments and days. The tool facilitates the identification of unusual market patterns, particularly in the context of potential manipulative behaviors, such as *spoofing*. Built with **Python**, utilizing libraries such as `Plotly`, `Plotly-Resampler`, and `Dash`, the visualization supports seamless interactions including zooming, filtering, hovering, and drill-down features. The tool is optimized for scalability, supporting exploratory analysis of large datasets and enhancing the interpretability of complex market dynamics.

Keywords: Limit Order Book, Visualization, Interactive Tool, Market Behavior, Python, Plotly, Data Exploration

1. Introduction

Modern financial markets generate vast volumes of data at extremely high speeds. Among the most information-rich sources is the **Limit Order Book** (*LOB*), which records all buy and sell orders placed on an exchange. This data reflects the full state of the market at any given moment and serves as a critical input for traders, regulators, and analysts alike. However, due to its high dimensionality, granularity, and temporal volatility, *LOB* data remains difficult to interpret without specialized tools.

While algorithmic approaches – particularly those rooted in *machine learning* – have made significant progress in tasks such as *anomaly detection* and *fraud identification*, they often lack interpretability. In contrast, interactive visualization can offer domain experts a complementary way to explore, understand, and hypothesize about trading patterns. One important use case is the detection of **spoofing**, an illegal practice in which traders place large deceptive orders to manipulate market prices. Identifying such behaviour in historical data remains a challenge, not only computationally but also in terms of human interpretability.

In this work, I present a visual analytics tool tailored for exploratory analysis of historical *LOB* data. The system is designed to help users:

- Interactively explore high-frequency time series data.
- Visualize order flow dynamics and price evolution.
- Identify patterns that may suggest manipulative behaviour.

2. Related Work

Visual exploration of *Limit Order Books* data has become an important component of modern financial analysis, particularly in the context of *high-frequency trading* and *market microstructure research*. A number of tools and platforms exist to support visualization of *LOB* dynamics; however, most are either proprietary, limited in scope, or not designed with multidimensional or anomaly-focused exploration in mind.

Among proprietary tools, **A7 (Advanced Order Book)** by *Deutsche Börse* provides sophisticated visualizations of order book depth and order flow, enabling traders to identify key liquidity levels and market activity in real time [1]. Similarly, **Bookmap** offers an interactive, time-based heatmap of liquidity that visualizes

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how market depth changes at different price levels, allowing users to track the behaviour of large market participants [2]. **NinjaTrader**, another widely used trading platform, supports real-time visualization of market depth and liquidity, targeting professional and institutional traders [3]. While these tools are powerful, their proprietary nature limits their adaptability for academic or exploratory research purposes. Moreover, they are primarily designed for operational decision-making and **trading**, not for retrospective analysis or anomaly detection.

In the open-source domain, **QuantConnect** provides infrastructure for backtesting algorithmic strategies and includes tools for visualizing historical order book data [4]. Meanwhile, **Lightweight Charts** is a flexible, browser-based library that allows developers to build interactive financial charts with low overhead [5]. Although these tools are more accessible for research and development, they generally focus on traditional charting or single-instrument time series and do not natively support multi-dimensional visual exploration across multiple trading days, instruments, or anomaly types.

A common limitation across all these tools – regardless of openness or proprietary status – is their emphasis on **single-instrument**, **short-term visualization**, often constrained to one trading day or one market product at a time.

The visualization tool presented in this work addresses these gaps by enabling interactive exploration of *multivariate*, *multi-instrument*, and *multi-day* LOB data, with.

3. Methods

The architecture and workflow of the proposed system reflect three main stages: **data preprocessing**, **visual encoding**, and **interactive exploration**. This section describes each component in detail.

The visualization tool was implemented in **Python 3.11**. Key libraries used include `Plotly` for rendering interactive plots, `plotly-resampler` for dynamic downsampling of large time series, and `Dash` for building the web-based dashboard interface. Together, these technologies enable responsive, scalable exploration of high-frequency financial data.

3.1. Data Source and Preprocessing

The main data source consists of historical market activity accessed via the **A7 API** provided by *Deutsche Börse*. Selected trading days and products were downloaded for analysis, including full order flow and order book event streams. Additional proprietary datasets were provided under a non-disclosure agreement (*NDA*) for research purposes.

Preprocessing involved parsing raw message-level trading data and reconstructing the full *Limit Order Book* (LOB) for each point in time. For consistency and portability, the resulting order book snapshots were stored in a format called **LOBSTER** – representing price levels, volumes, and event types in a structured CSV format [6].

Several derived features were computed during this phase, including:

- **Imbalance Index:** Ratio between bid and ask volumes over the top price levels.
- **Message Frequency:** Number of incoming messages (additions, moddifications, cancellations, executions) per time window.
- **Cancellation Frequency:** Subset of the message frequency corresponding specifically to order cancellations.

These features not only enhance visual interpretability but also serve as input for anomaly detection models in later stages of the broader research.

3.2. Visual Design and Encoding

The visualization interface integrates two complementary views designed to support both broad pattern discovery and detailed inspection:

- **Price Chart:** A multivariate time-series plot displaying the price evolution of a selected instrument over a trading day, alongside derived indicators such as imbalance index and message frequencies. Multiple Y-axes allow distinct data dimensions to be plotted simultaneously.
- **Heatmap Matrix:** A compact, time-aligned heatmap that aggregates selected metrics across many instruments and trading days. The X-axis represents time (e.g. hourly bins), the Y-axis represents day-product combinations, and the color scale encodes the aggregated metric (e.g., average of imbalance or standard deviation of price).

The chart and heatmap work in tandem: users can identify high-level patterns in the matrix and drill down into specific time slices via the price chart for more detailed analysis.

3.3. Interaction Techniques

Interactivity is central to the tool's design, allowing users to fluidly navigate the temporal and dimensional complexity of LOB data. Supported interactions include:

- **Details-on-Demand:** Clicking a heatmap row loads the corresponding detailed price chart for the selected day and instrument.
- **Hover Linking:** Hovering over the heatmap highlights the corresponding time interval in the price chart, providing contextual linking between views.
- **Synchronized Zooming:** Panning or zooming in the price chart triggers an update in the heatmap view to maintain temporal alignment.
- **Dynamic Filtering:** Users can filter individual series in the chart (e.g., toggling visibility of imbalance or cancellation frequency), and reconfigure the heatmap to display different metrics, aggregation functions (mean, median, maximum, minimum, standard deviation), or time granularities in seconds (from 1 minute to 12 hours).

These features aim to support **visual hypothesis generation**, allowing analysts to quickly form and test ideas about potential market manipulation or unusual activity patterns.

4. Results and Discussion

Figures 1 and 2 illustrate the dashboard interface in use. Figure 1 displays the default view, featuring a multi-metric price chart and the corresponding heatmap. Figure 2 highlights interactive features such as filtering the chart to display only the top price level, changing heatmap aggregation methods, and using the hover interaction for temporal alignment.

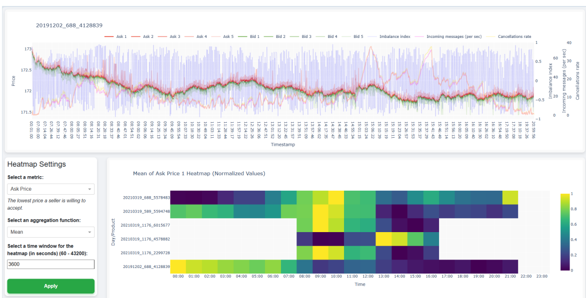

Figure 1: Default dashboard view with full price chart and heatmap visualization

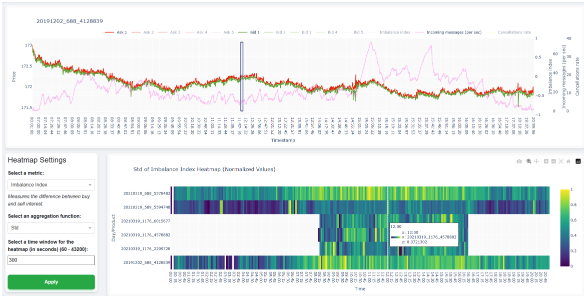

Figure 2: Dashboard showing filtered chart and interactive hover-based alignment

Figures 3 and 4 offer a closer examination of the time-series price chart. The first displays all five price levels alongside the imbalance index and message frequencies. The second presents a simplified version with only the top-level price and message frequency shown, demonstrating the tool's flexible filtering capabilities.

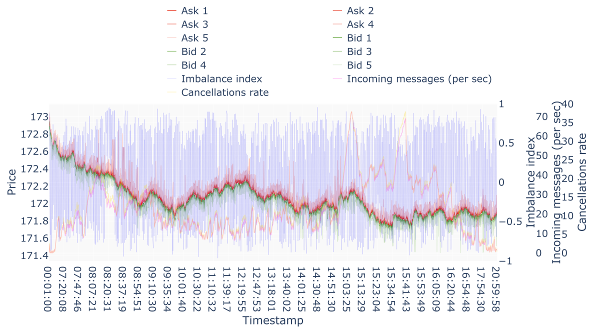

Figure 3: Comprehensive price chart including five price levels, imbalance index, and two message frequency metrics

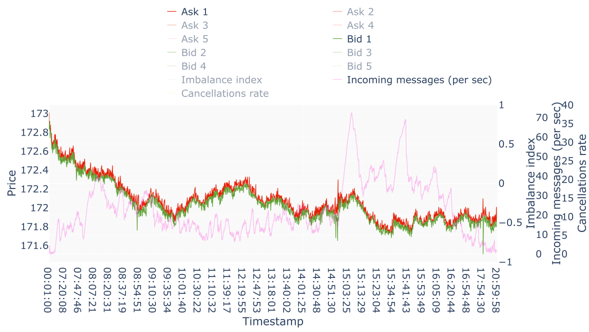

Figure 4: Filtered price chart showing only the top price level and message frequency

These visualizations enable rapid assessment of market activity, identification of high-frequency trading patterns, and contextual investigation of anomalies.

The heatmap effectively highlights temporal outliers or bursts of unusual behavior, guiding users to specific regions of interest. Follow-up inspection using the detailed price chart supports hypothesis generation.

5. Conclusion

This work presented an interactive visual analytics tool designed to explore high-frequency *Limit Order Book* (LOB) data, with a particular focus on detecting anomalies and market manipulation behaviors such as *spoofing*. By integrating flexible visual encoding and interaction mechanisms, the tool enables users to both identify patterns across multiple instruments and timeframes and to drill down into detailed, time-aligned views of market data.

Through its dual-view design – consisting of a price chart and heatmap matrix – the tool provides a comprehensive and intuitive interface for analyzing complex market dynamics. Interactivity features, including hover linking, details-on-demand, and synchronized zooming, facilitate rapid exploration and hypothesis generation, offering support for both macro- and micro-level insights.

5.1. Future Work

Despite its strengths, the system has certain limitations. Scalability remains constrained by memory requirements: loading multiple days or many instruments simultaneously can exceed RAM capacity, especially when working with high-resolution data. Future versions could benefit from integration with disk-based data stores or stream processing tools to handle larger datasets.

Additionally, while the interface has been designed for usability, formal evaluation with domain experts (e.g., financial analysts or regulators) is needed to assess real-world effectiveness and improve interaction design. Features such as saved views, annotation tools, or integration with anomaly detection models could further enhance the platform's analytical utility.

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