Foundation Models for Spatio-Temporal Data Science

A Survey Overview

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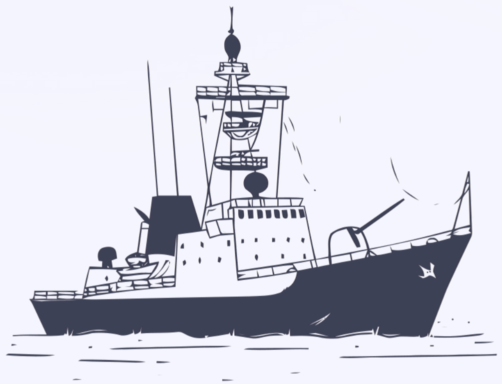
Why Spatio-Temporal Data Matters

The Challenge

Traditional MLmodelsstruggle with data that has both spatial and temporal dimensions. Real-world systems are dynamic, location-dependent, and evolving.Foundation models offer a breakthrough approach to understanding complex spatio-temporal patterns.



Weather Forecasting

Predicting climate patterns across regions and time

Traffic Management

Real-time urban flow optimization

Human Mobility

Understanding movement patterns at scale

Spatio-Temporal Data Types

Locations

Point-based geographic coordinates with temporal stamps

Trajectories

Sequential movement paths capturing mobility over time

Events

Discrete occurrences at specific locations and times

ST Raster Grids

Gridded spatiotemporal data like satellite imagery

ST Graphs

Connectedspatial entities evolving through time

What Are Foundation Models?

Definition

Large-scale pre-trained models capable of adapting to diverse downstream tasks with minimal fine-tuning.

Core Strengths

- Generalization across domains
- Rapid task adaptation
- Multi-modal capabilities
- Transfer learning efficiency

1

GPT Series

Natural language understanding and generation at scale

2

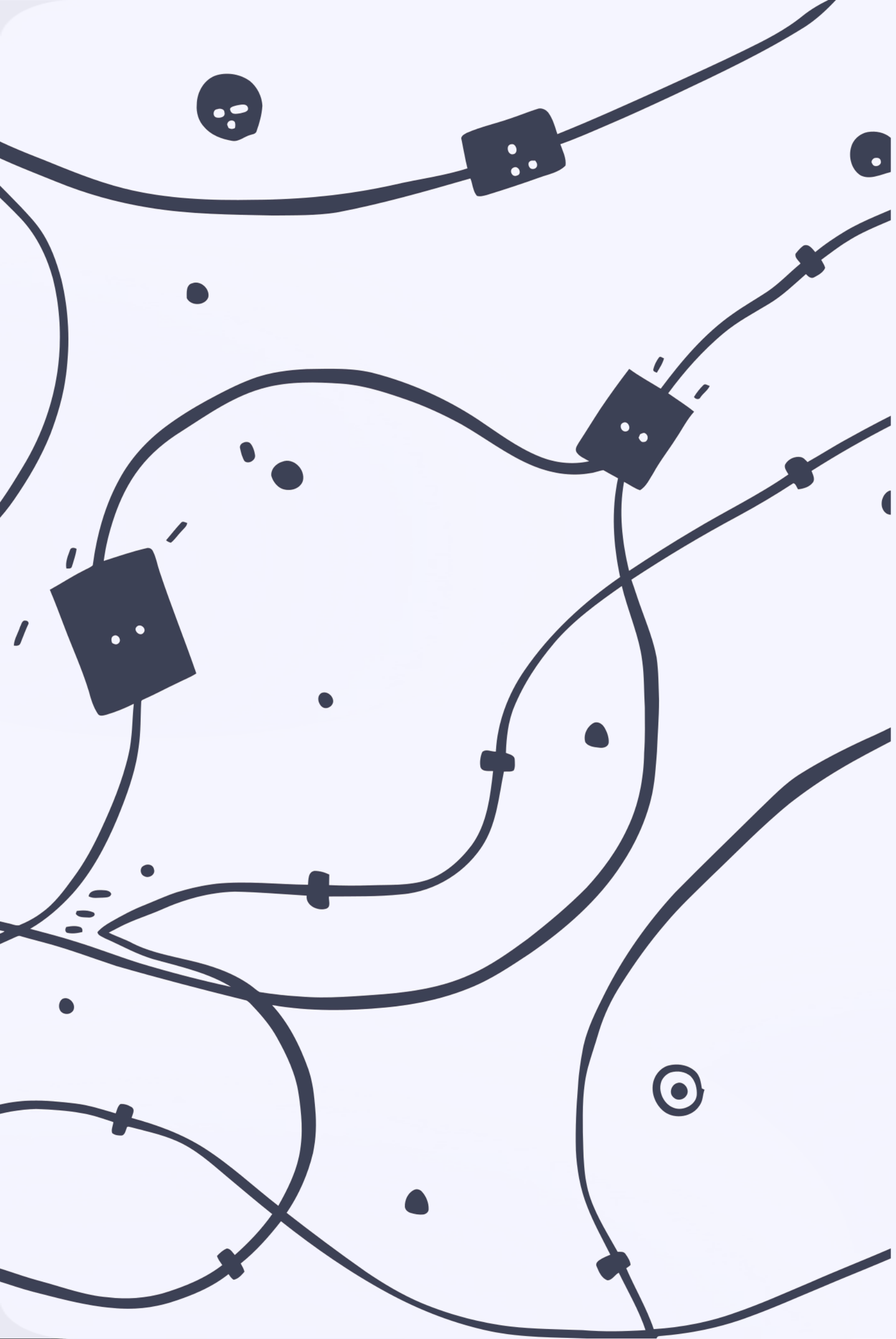
BERT

Bidirectional context encoding for NLP tasks

3

CLIP

Vision-language alignment for multi-modal learning



Spatio-Temporal Foundation Models (STFMs)

What Makes STFMs Different?

STFMs extend foundation model principles to spatial and temporal dimensions, enabling unprecedented understanding of location-time dependencies.

They learn universal representations of how phenomena evolve across space and time.

Traditional Models

Task-specific, limited generalization

STFMs

Universal, adaptable, context-aware

STFM Workflow Pipeline

The complete lifecycle ofspatio-temporalfoundation modelsfollows four integrated stages, from data collection through real-world application.

1. ### ST Data Sensing
   Real-world and synthetic data collection
2. ### ST Data Management
   Cleaning, imputation, and organization
3. ### ST Data Mining
   Pattern discovery and model training
4. ### Applications
   Deployment in real-world systems

Stage 1 & 2: Data Sensing and Management

Stage 1: ST Data Sensing

Real-World Sensing

- GPS trajectories
- Sensor networks
- Satellite imagery

Synthetic Generation

- Trajectory-LLM
- LLMob
- Simulation systems

Stage 2: ST Data Management

01

Data Cleaning

Noise removal and quality assurance

02

Imputation

Filling missing spatio temporal gaps

03

Retrieval Systems

PLMTrajRec, UrbanLLM

04

Knowledge Graphs

UrbanKGent integration

Stage 3: ST Data Mining

Perception

Understanding Patterns

- STEP: Spatial-temporal pattern recognition
- Pangu: Large-scale weather modeling
- Feature extraction from complex ST data

Optimization

Decision-Making Agents

- AgentMove: Intelligent mobility optimization
- Resource allocation algorithms
- Dynamic routing and scheduling

Reasoning

Causal&Numerical Analysis

- UrbanGPT: Urban context understanding
- NuwaDynamics: Temporal causality
- GCIM: Graph-based inference

Real-World Applications

Numerical Applications

- Forecasting

  Predicting future spatio temporal states

- Anomaly Detection

  Identifying irregular patterns in ST data

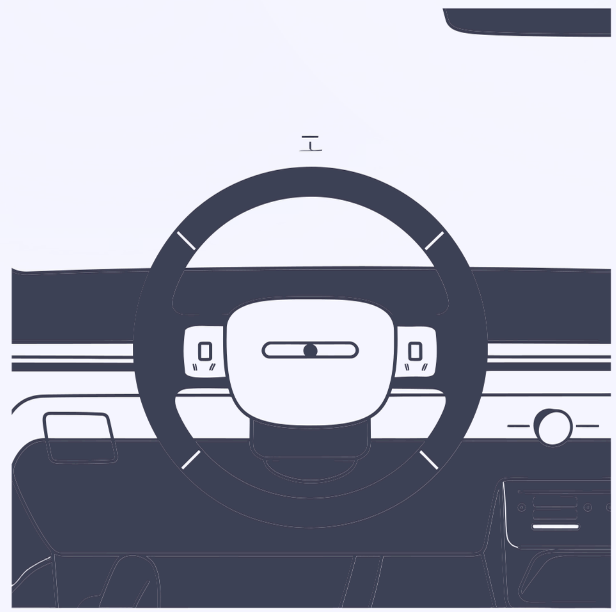
- Event Analysis

  Understanding occurrence patterns

- Geo-Localization

  Precise spatial positioning and tracking

Inferential Applications



→ Traffic Control Systems

→ Autonomous Vehicles

→ Disaster Response

→ Scenario Simulation

Representative Models & Future Challenges

Leading STFM Architectures

LLM-Based Models

UrbanGPT, TrafficGPT, GeoGPT

Pre-trained Foundation Models

Pangu, ClimaX, UniST, TrajFM, UrbanDiT

Key Challenges Ahead

Interpretability

Understanding model decisions

Multimodality

Integrating diverse data sources

Scalability

Handling planetary-scale data

Universal STFM

One model for all ST tasks

> STFMs represent a paradigm shift in how we understand and interact with spatio-temporal data, enabling intelligent systems that perceive, reason about, and act upon the dynamic world around us.

Summary & Key Takeaways

- Spatio-temporal data is essential for understanding dynamic real-world systems such as weather, traffic, and human mobility.

- Foundation Models (FMs) introduce a new paradigm by enabling models to generalize across domains with minimal training.

- STFMs (Spatio-Temporal Foundation Models) extend this to spatial + temporal data, integrating perception, optimization, and reasoning into a single framework.

- The STFM workflow unifies data sensing, management, mining, and application – covering the entire lifecycle of ST data science.

- Real-world applications include climate forecasting, anomaly detection, mobility prediction, disaster response, and intelligent city planning.

- STFMs represent a transformative step toward general-purpose, multimodal, cross-domain AI for understanding complex physical systems.

My Perspective

- STFMs feel like the natural evolution of machine learning – they move beyond specialized models and toward universal models that understand the world across space and time.

- I found the idea compelling that STFMs can support the entire data pipeline (from sensing → management → mining → decisions), unlike traditional ML models that only handle one part.

- The biggest challenge I see is interpretability. These models are extremely powerful, but understanding why they made a prediction is still difficult.

- I believe the most immediate impact of STFMs will be in urban computing, climate modeling, and transportation systems, where data is complex and constantly changing.

- Overall, STFMs highlight how AI is evolving from tools that predict to systems that can perceive, reason, and act – a major step toward intelligent, data-driven cities and environments.

Thank You!!

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