GeoAI & Urban Digital Twin: Opportunities and Challenges for Realistic, On-Time Analysis and Situational Awareness

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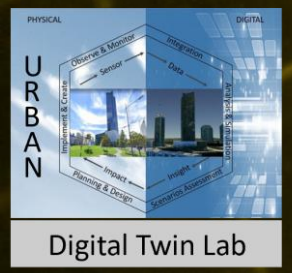
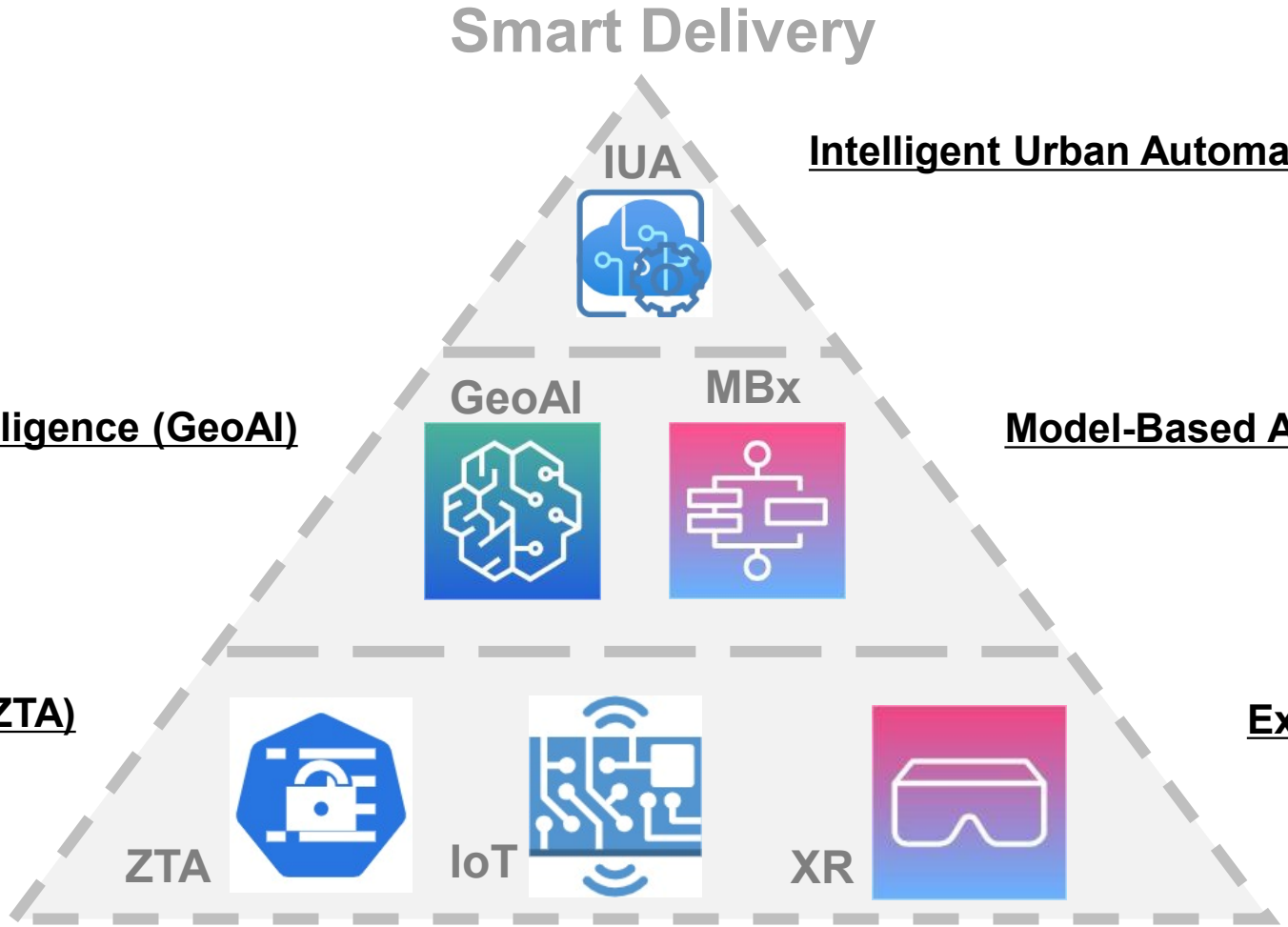


Agenda

- Introduction
- Global Challenges and Complex Environments
- Urban Digital Twin & GeoAI
- Application Areas
- Conclusion & Next Steps

Introduction

Urban Digital Twin (UDT) - Lab



Intelligent Urban Automation (IUA)

Geospatial Artificial Intelligence (GeoAI)

Model-Based Anything (MBx)

Zero Trust Architecture (ZTA)

Extended Reality (XR)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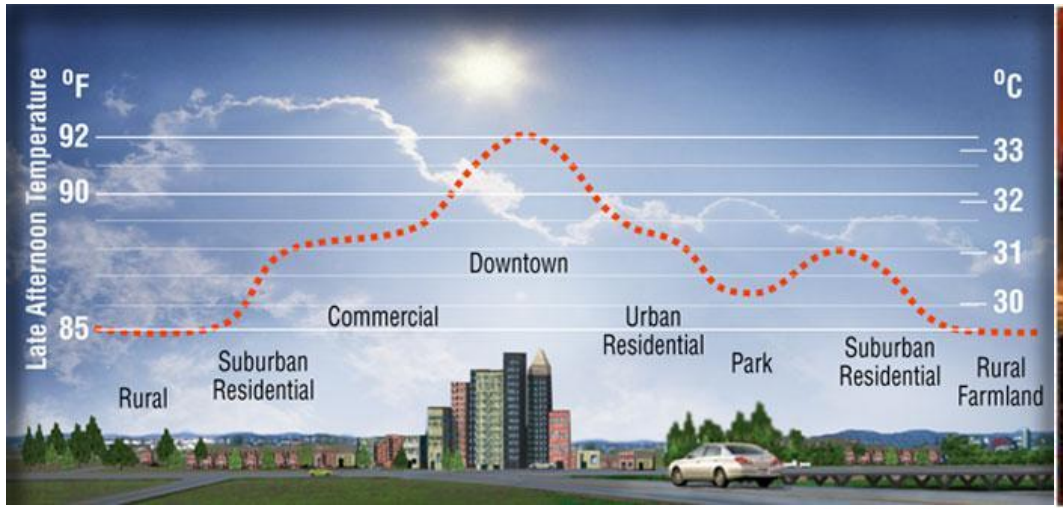
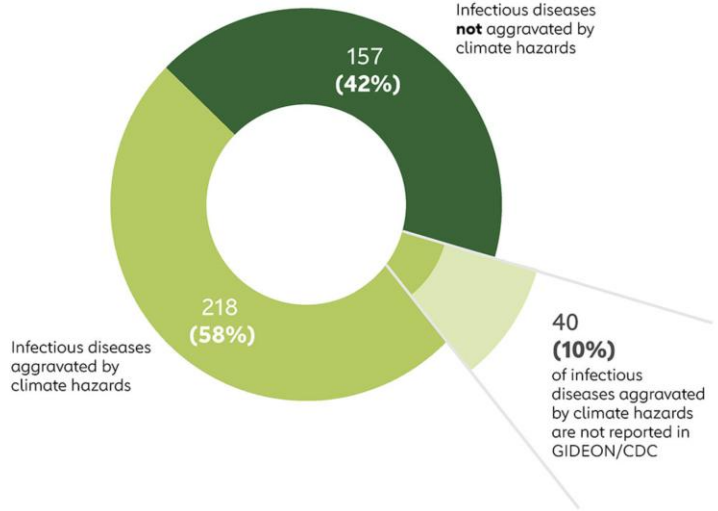
Global Challenges & Complex Environments

Global Challenges…

Digital Twin Lab





Adapted from Figure 4. Mora, C., McKenzie, T., Gaw, I.M. et al. Over half of known human pathogenic diseases can be aggravated by climate change. Nat. Clim. Chang. (2022). https://doi.org/10.1038/s41558-022-01426-1

USGS science for a changing world

U.S. Department of the Interior
U.S. Geological Survey

Image From: U.S. Geological Survey Circular 1383–E
https://pubs.usgs.gov/circ/1383e/circ1383-E.pdf

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Complex Environments

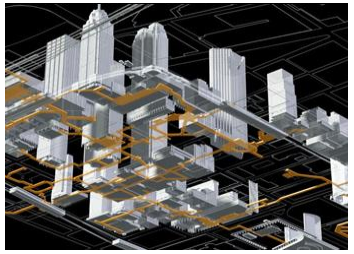
A primary reason for the limitations in addressing the interdisciplinary challenge of sustainability is the **lack of an ecosystem of open, harmonized and interoperable information models and datasets across Infrastructure, built and natural environments**.

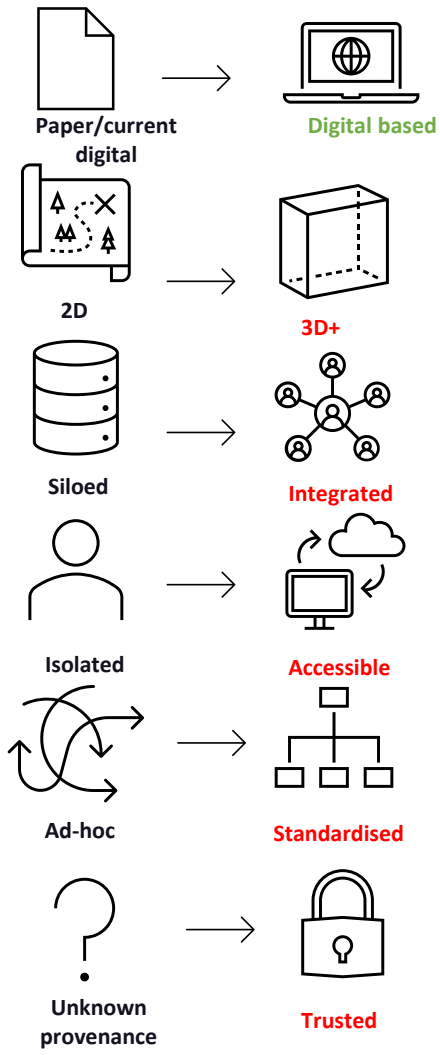






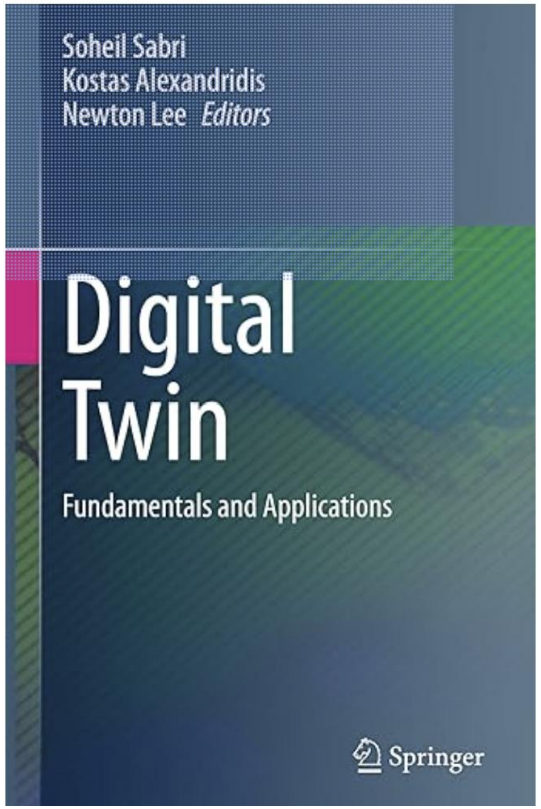




Urban Digital Twin

Digital Twin Fundamentals



Sabri, S., Alexandridis, K., Lee, N. (2024). Introduction to Digital Twins. In: Sabri, S., Alexandridis, K., Lee, N. (eds) Digital Twin. Springer, Cham. https://doi.org/10.1007/978-3-031-67778-6_1

Definition of a Digital Twin

David McKee, Counterpoint Technologies
Justin Piwetz, BP
Dan Isaacs, Digital Twin Consortium

digital twin CONSORTIUM

A digital twin is an **integrated data-driven virtual representation** of **real-world entities and processes**, with **bidirectional synchronized interaction** at a specified frequency and fidelity.

Digital Twins are motivated by outcomes, driven by use cases, powered by integration, built on data, **enhanced by physics**, guided by domain knowledge, and implemented in **dependable and trustworthy IT/OT/ET systems**.

- Digital Twin Systems transform business by **accelerating and automating** holistic understanding, continuous improvement, decision making, and interventions through effective actio
- **Digital Twin Systems** are built on integrated and synchronized IT/OT/ET systems, use **real-time and historical data** to represent the past and present and **simulate predicted futures**.
- **Digital Twin Prototypes** use data to model and simulate predicted futures before being integrated into IT/OT/ET Systems and before synchronization with the real-world entity or process.

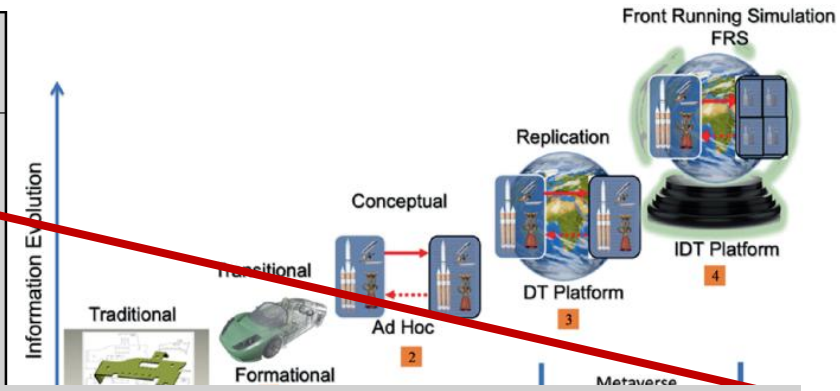
The Digital Twin Consortium's definition of a digital twin is comprised of three primary elements:

1. Integrated data-driven virtual representation, including both structured and unstructured data.
2. Real-world entities and processes which emphasizes the importance of the environment in which the systems operate, often incorporating associated physics.
3. Bidirectional synchronized interaction, which should be appropriate for the use case and may therefore be have periodic, aperiodic, or sporadic frequencies that may also differ depending on the synchronization

ensure comprehensive linkage across isolated data repositories and systems, enabling safe and secure closed-loop communication across products, people, processes, and place.

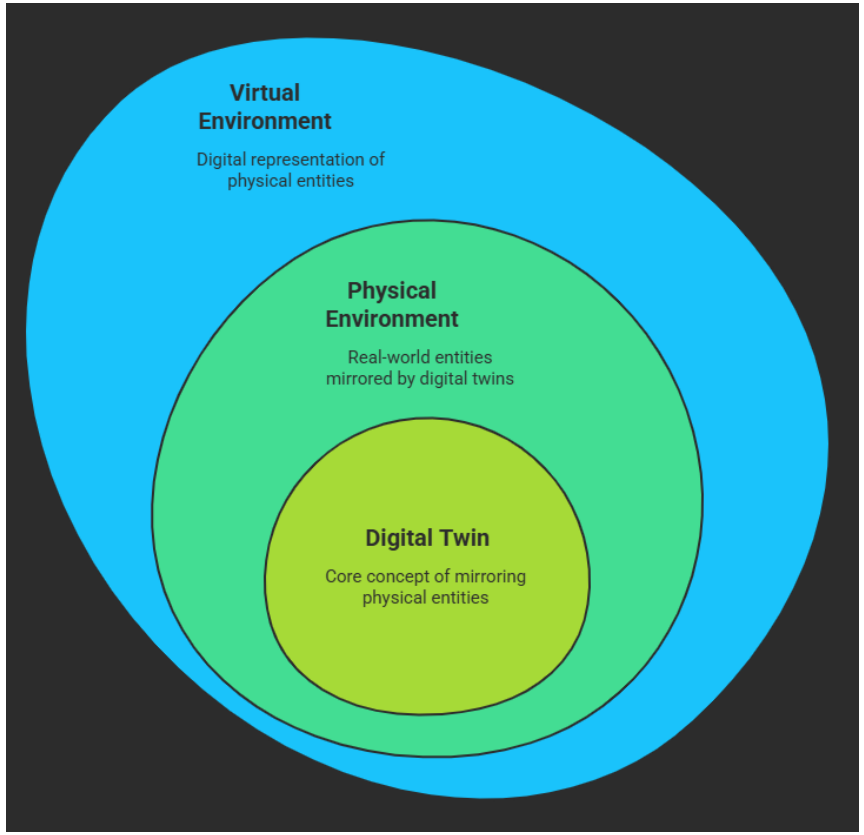
The development of this definition was supported by:

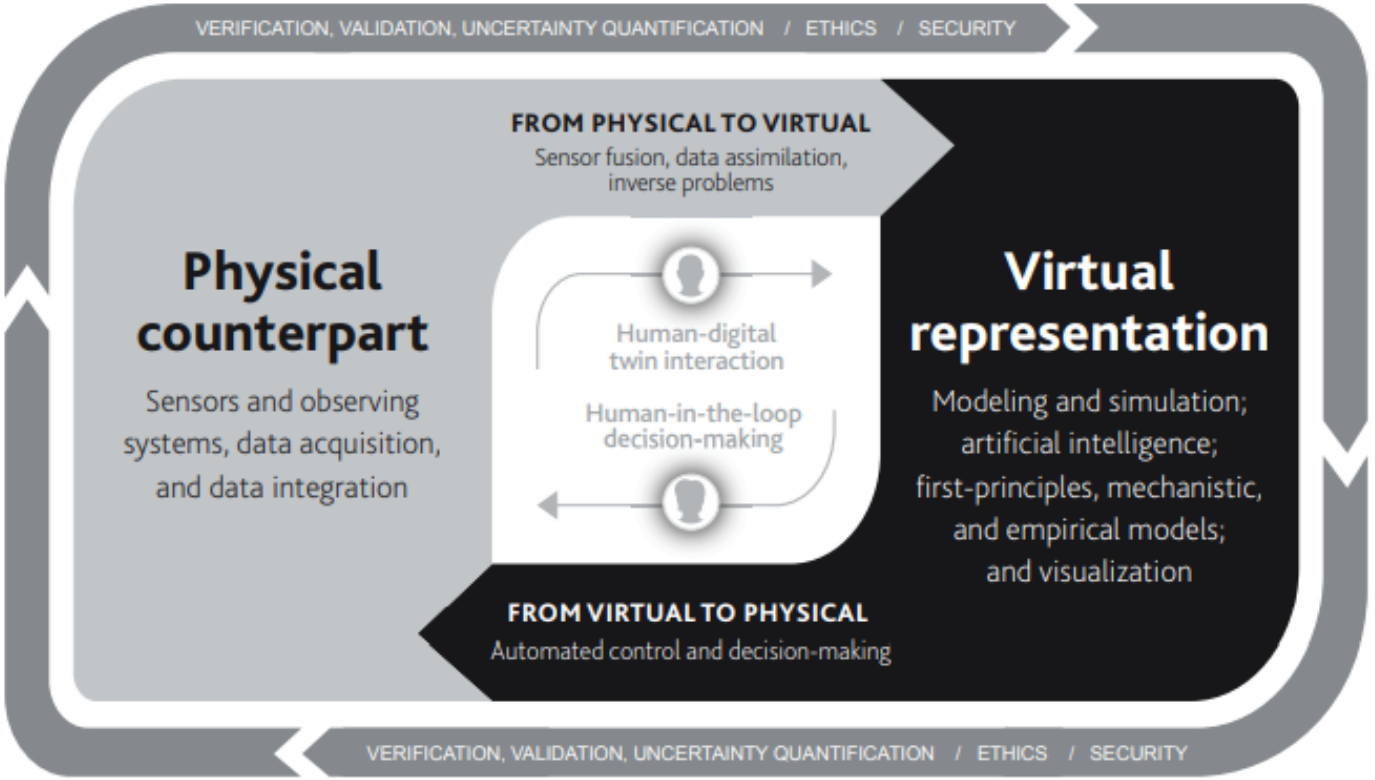
Chafia Aouissi (Microsoft), Chandra Challagonda (FIWARE), Dave Shaw (Intuitus), Dennis Dokter (University of Leeds), Detlev Richter (TUV), Emory Hodges (Lockheed Martin), Greg Porter (Sev1tech), Liang Downey (Microsoft), Lionel Beneteau (SLB), Mark Boyle (Digital Catapult), Marlon Rodgers (Lockheed Martin), Michael Grieves (Digital Twin Institute), Michael Loughlin (Digital Catapult), Pete Mills (Crysp), Pieter van Shalkwyk (XMPro), Robert Martin (Mitre), Said Tabet (Dell Technologies), Sian Purver (Crysp), and Soheil Sabri (University of Central Florida)



A digital twin is an **integrated data-driven virtual representation** of **real-world entities and processes**, with **bidirectional synchronized interaction** at a specified frequency and fidelity.

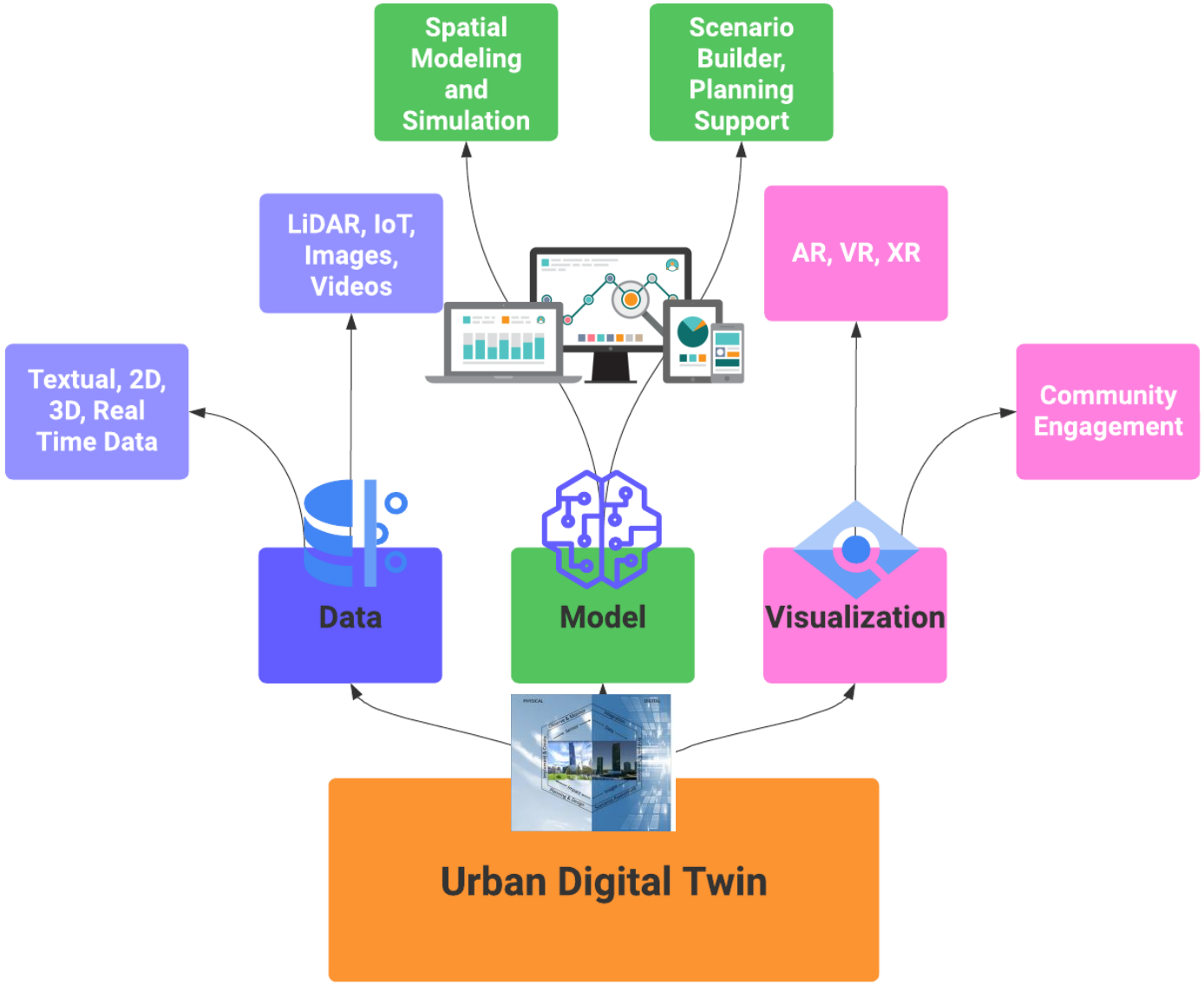
Elements of Digital Twin





https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins

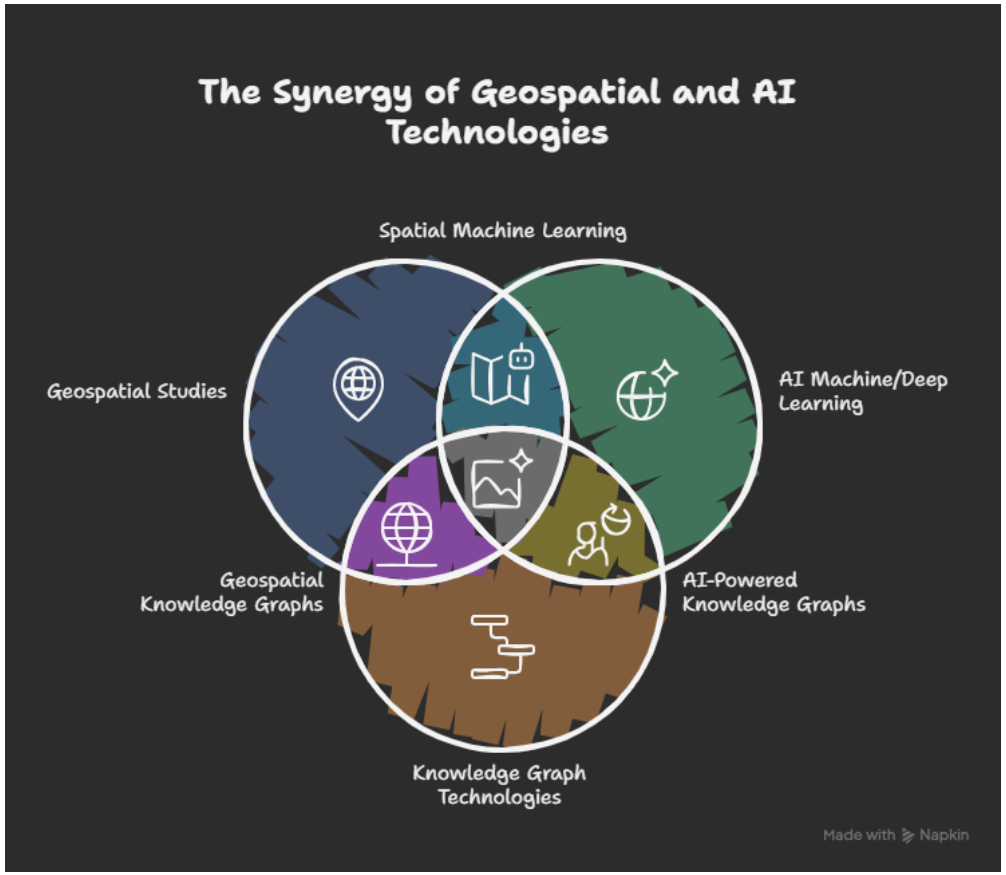
Design Philosophy: A Highly Composable, Customizable, and Open Ecosystem



- **Composable Architecture** – Modules can be configured based on needs
- **Customizable Interface** – Tailored for local and regional requirements
- **Open Ecosystem** – Integration with third-party tools, data sources, and models
- **Scalable & Adaptable** – Designed to evolve with emerging technologies
- **Supports Real-Time Decision-Making** – Enables evidence-based responses

GeoAI Definition

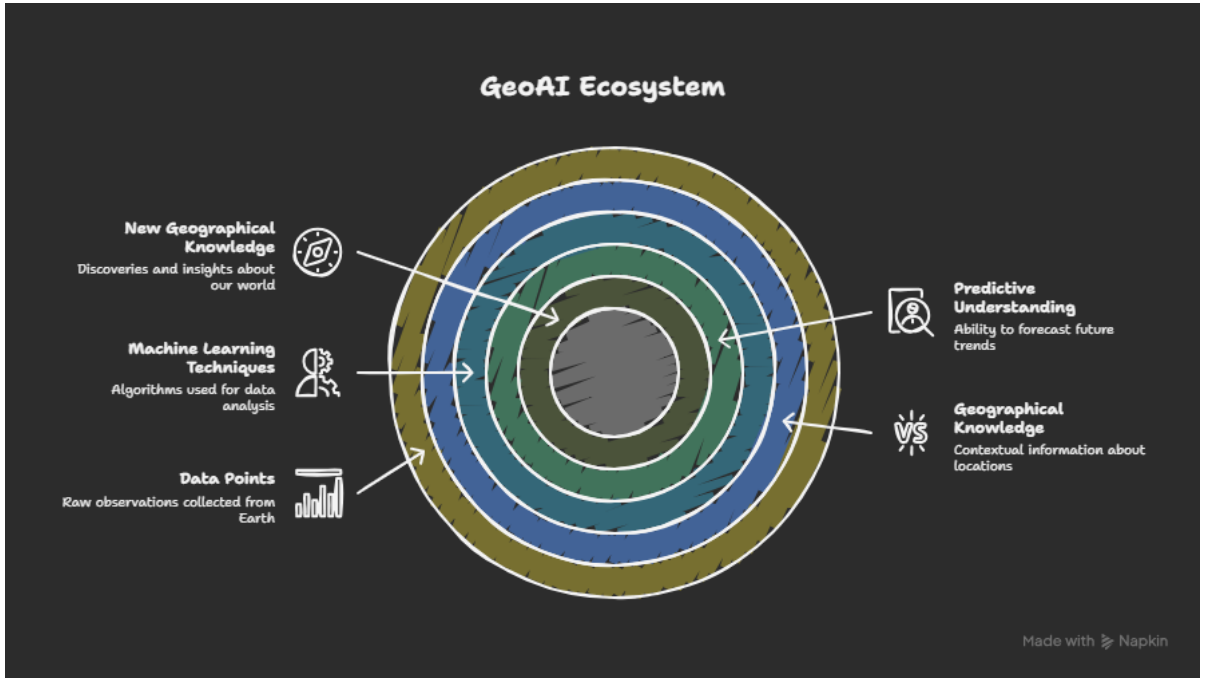
GeoAI, or **Geospatial Artificial Intelligence**, is defined as the integration of **geospatial studies** and **AI machine (deep)** learning and **knowledge graph** technologies. It is recognized as an interdisciplinary field and a fast-emerging domain.



Li, Song Gao, Yingjie Hu, Wenwen, ed. 2023. *Handbook of Geospatial Artificial Intelligence*. Boca Raton: CRC Press.

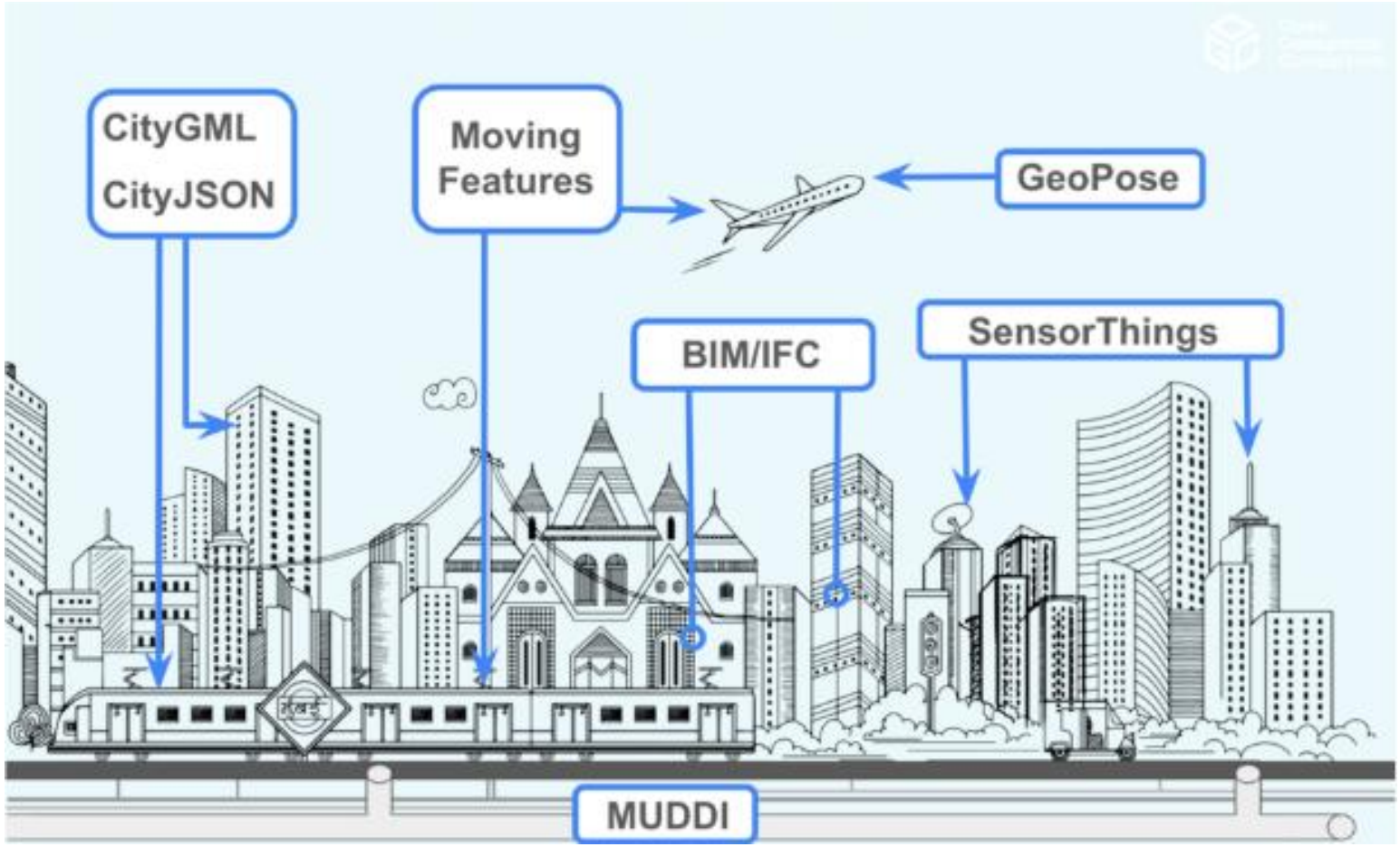
GeoAI – Empowering GIScience

- GeoAI is like a modern-day specialized telescope built specifically for Earth science;
- Instead of just seeing data points (like stars), it integrates geographical knowledge and high-powered machine learning techniques (the lenses) to
  - Perceive patterns,
  - Reason about location, and
  - Discover new geographical knowledge (new planets and galaxies),
- Moving beyond simple observation to gain a **deeper**, **predictive** understanding of our world.



Li, Song Gao, Yingjie Hu, Wenwen, ed. 2023. *Handbook of Geospatial Artificial Intelligence*. Boca Raton: CRC Press.

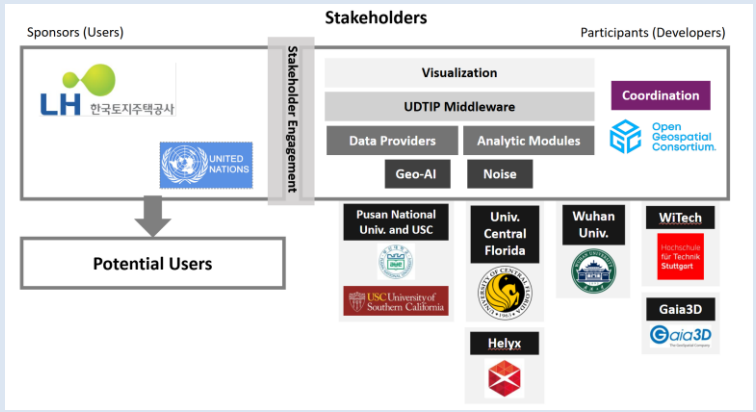
Urban Digital Twin Components - OGC

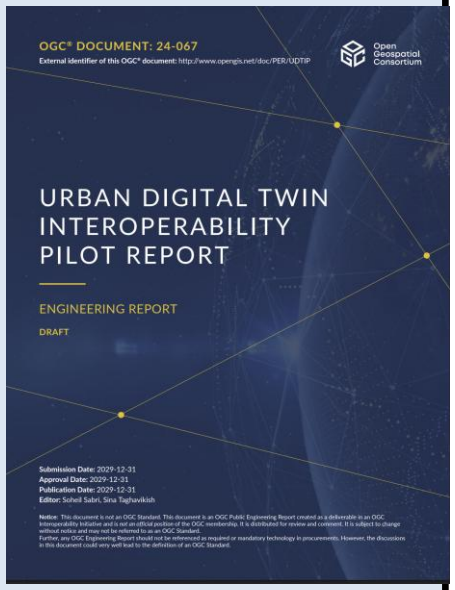


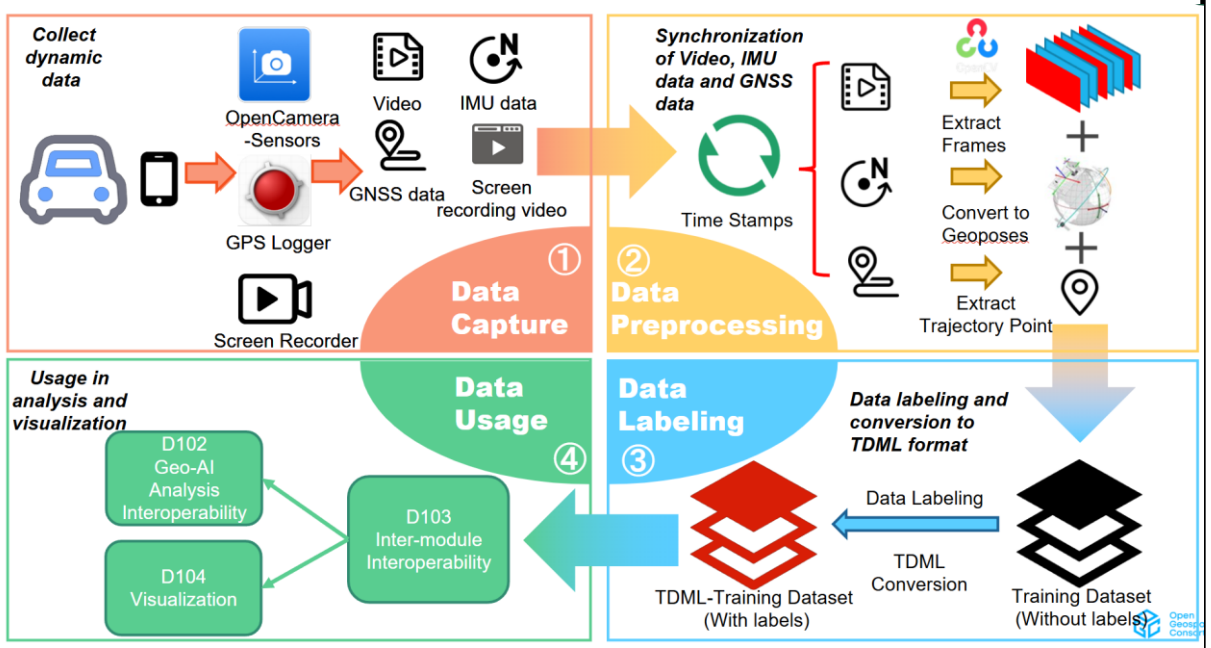
https://docs.ogc.org/dp/24-025.html

Urban Digital Twin Interoperability – GeoPose and GeoAI

Urban Digital Twin Interoperability







Objectives, Approach

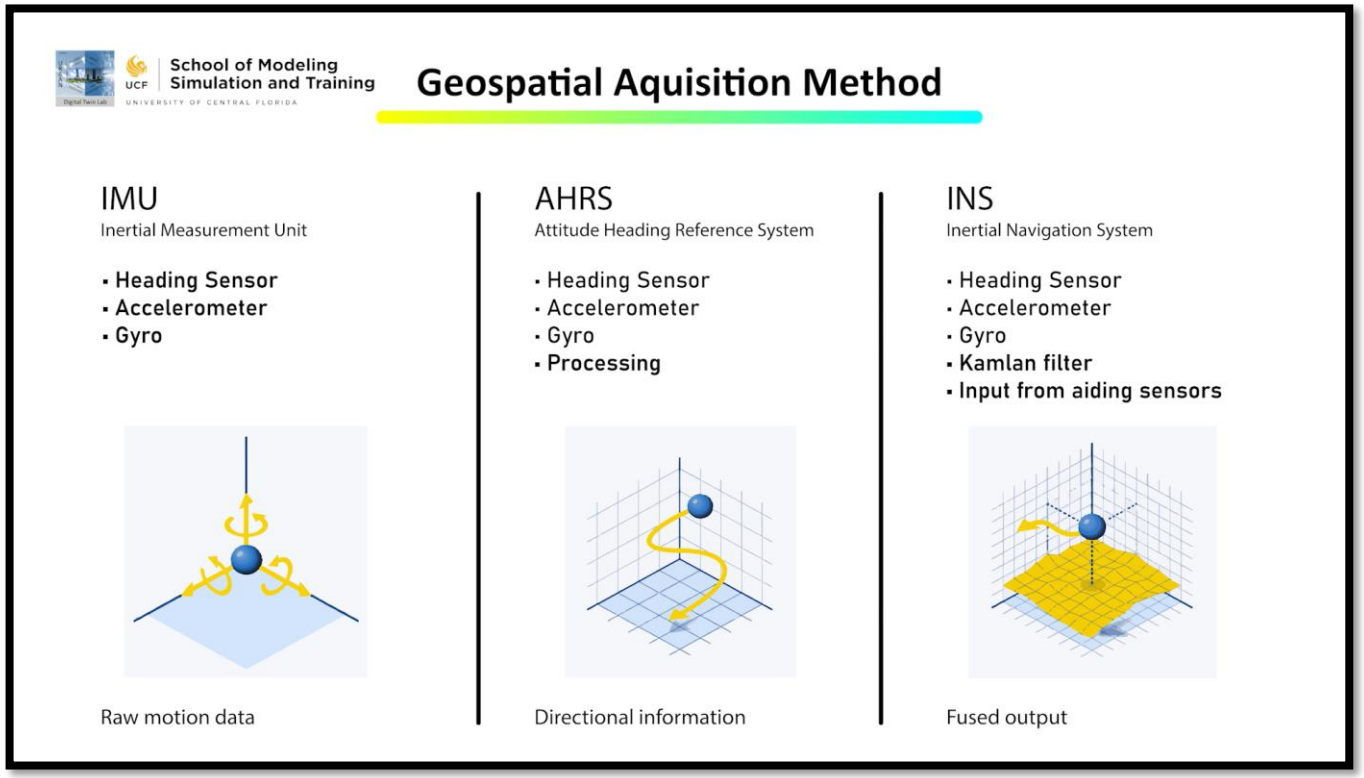
- This project develops an Urban Digital Twin (UDT) framework using OGC standards to improve data interoperability and system integration.
- It focuses on noise modeling (using 3D city models and sensor data) and Geo-AI analysis (using camera imagery and machine learning for object detection).
- The project aims to create prototype APIs and tools, demonstrating how OGC standards can enable a robust and interoperable UDT ecosystem.

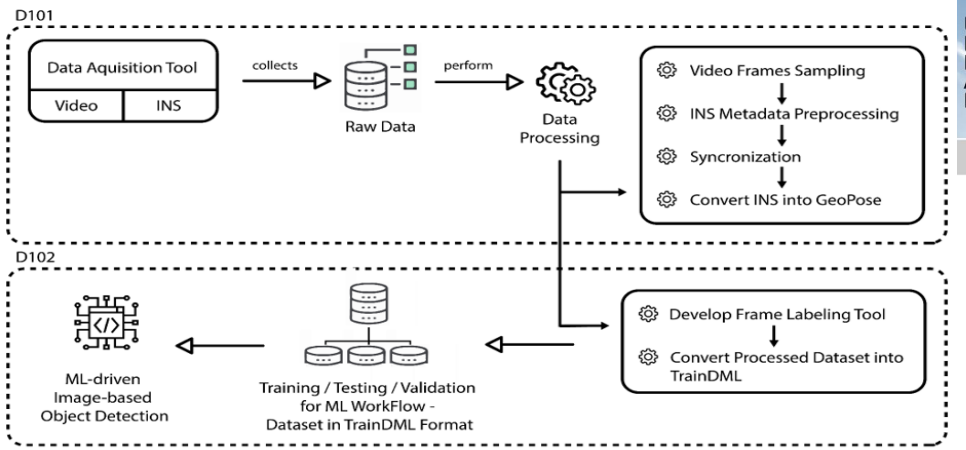
Impact, Outcomes, Achievements

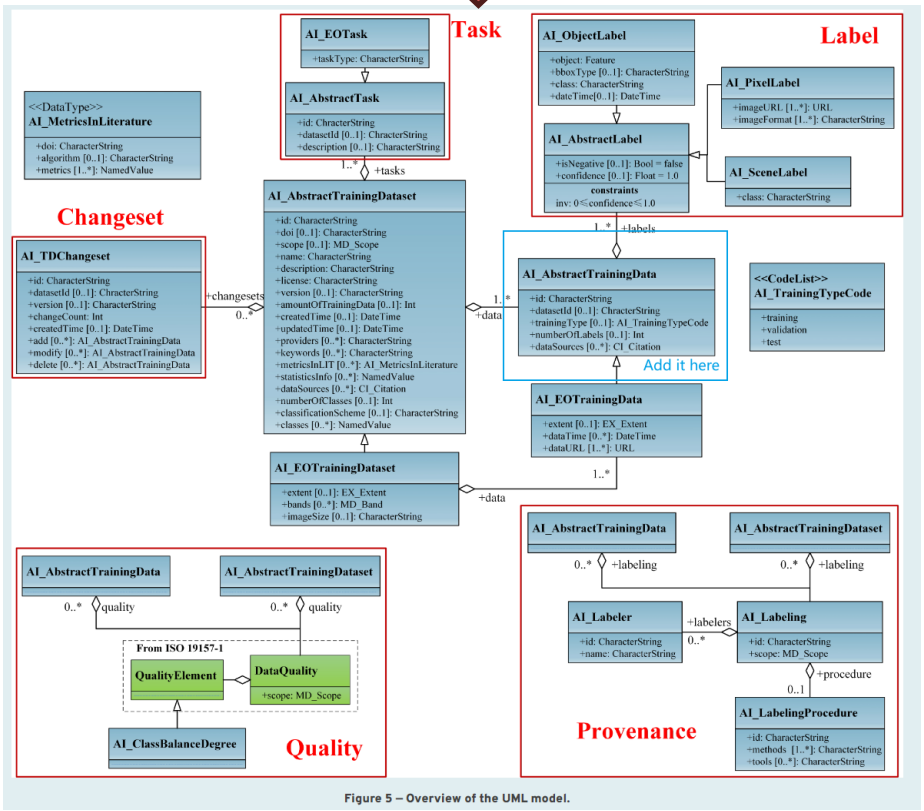
- Improved TrainingDML standard through adding Geopose (6Dof)
- Developed an applied workflow for geo-localizing low cost mobile camera recordings and images
- Used for the United Nations' Mission in Colombia for the classification of the road network in regional areas

Sabri, S., Taghavikish, S., 2025. Urban Digital Twin Interoperability Pilot Report (No. 24-067r1). Open Geospatial Consortium. https://docs.ogc.org/per/24-067r1.html

Image Synchronization



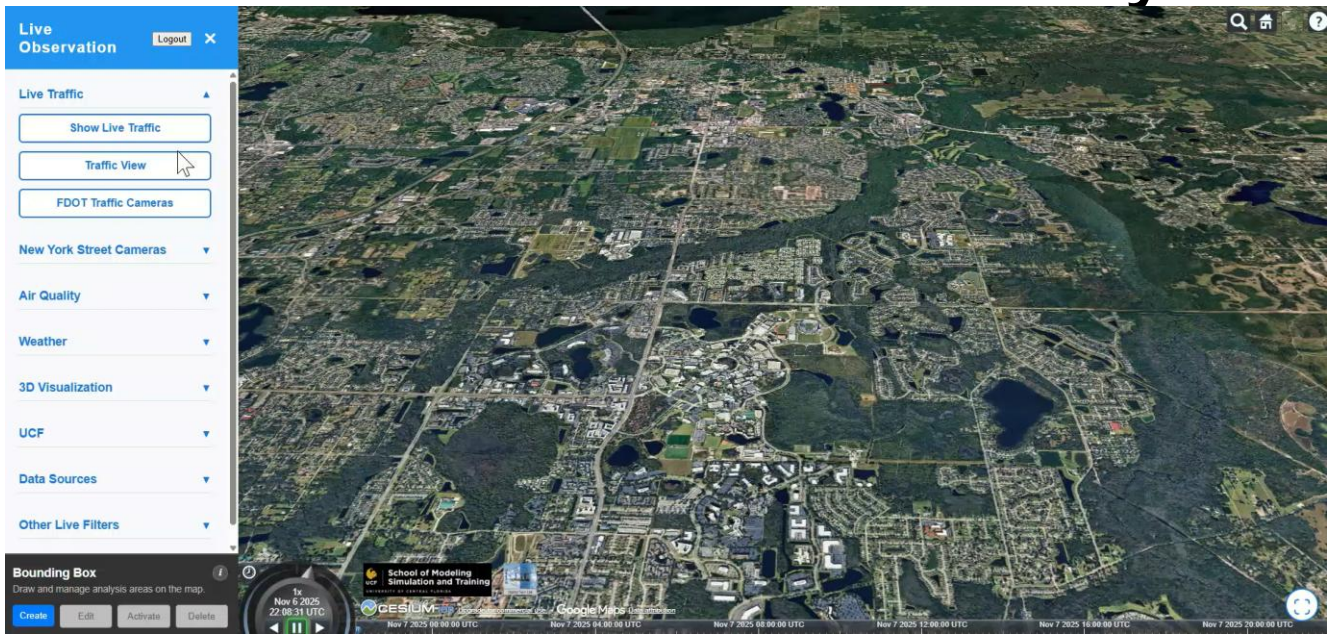


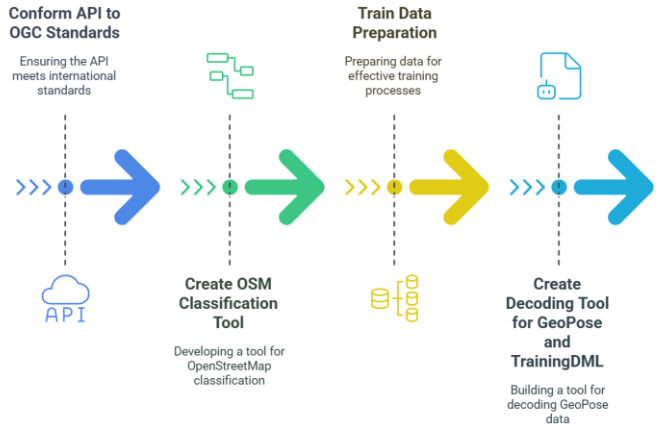


Thakar, K., Shervington, K., **Sabri, S.,** & Lee, B. (2025). GeoPose-enabled Camera Imagery Interoperability with GeoAI in Urban Digital Twins. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1427-2025

Image Segmentation, Object Classification, and Analysis

Digital Twin Lab





Pusan National Univ. and USC

USC University of Southern California

Univ. Central Florida

Wuhan Univ.

Helyx

Sabri, S., Taghavikish, S., 2025. Urban Digital Twin Interoperability Pilot Report (No. 24-067r1). Open Geospatial Consortium. https://docs.ogc.org/per/24-067r1.html

Autonomous Vehicles, Pedestrian Behavior and Built Environment

Methodological Framework

Three-phase approach connecting human movement with urban form

Phase 1: Human Pose Detection

- Video analysis for pedestrian behavior
- YOLOv8-Pose for detection
- ByteTrack for movement tracking

Phase 2: Sidewalk Geometry Extraction

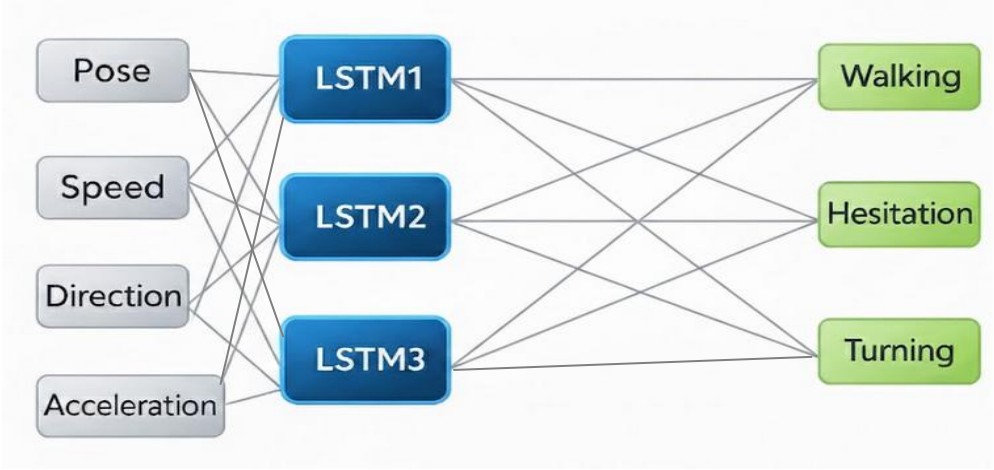
- Semantic segmentation
- Pixel-to-meter conversion
- CNN-based width estimation

Phase 3: Correlation Analysis

- Data fusion
- Heatmap generation
- Statistical modeling

"Connecting pedestrian behavior with urban form through data-driven analysis"

Behavior Modeling (LSTM)



LSTM Architecture

Sequential Processing

LSTM networks process pose data sequences to classify pedestrian behaviors.

Input Features

Joint positions, speed, direction, and acceleration from pose estimation.

Output Classifications

Walking, hesitation, and turning behaviors with confidence scores.

Key Advantage

LSTMs capture temporal dependencies in pedestrian movement patterns.

"Trained to classify walking, hesitation, and turning behaviors"

Sidewalk Segmentation

Semantic Segmentation

Process of classifying each pixel in an image into predefined categories.

- Used to detect sidewalk areas from urban imagery
- Creates pixel-perfect segmentation masks

BGR Color Mask

Color-based detection method for identifying sidewalk pixels.

Blue Green Red

Input Urban Imagery

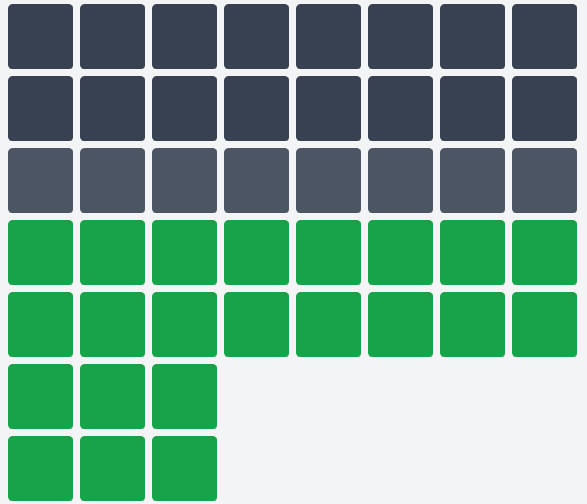
Segmentation Process

Input → Semantic Segmentation → Output

Detected Sidewalk Areas

Road

Sidewalk



Inferring Human Behaviors

Summary of Findings

Statistical correlation confirmed

Sidewalk Width & Behavior

Wider sidewalks lead to more relaxed pedestrian movement with reduced speed and increased lateral exploration.

Statistical correlation confirmed

Cross-context applicability

Spatial Geometry Consistency

Spatial geometric features show consistency across diverse urban contexts, enabling generalized models.

Cross-context applicability

High potential for city-wide analysis

Pose-based Modeling Scalability

Pose-based pedestrian modeling enables scalable city-wide behavioral analysis.

Potential for city-wide analysis

Pedestrian Comfort

Street width affects pedestrian comfort and movement relaxation.

Exploration Contexts

Wider sidewalks promote higher exploration and pedestrian engagement.

Exploration

Pedestrians in wider areas show greater lateral movement diversity.

AI-Based Motion

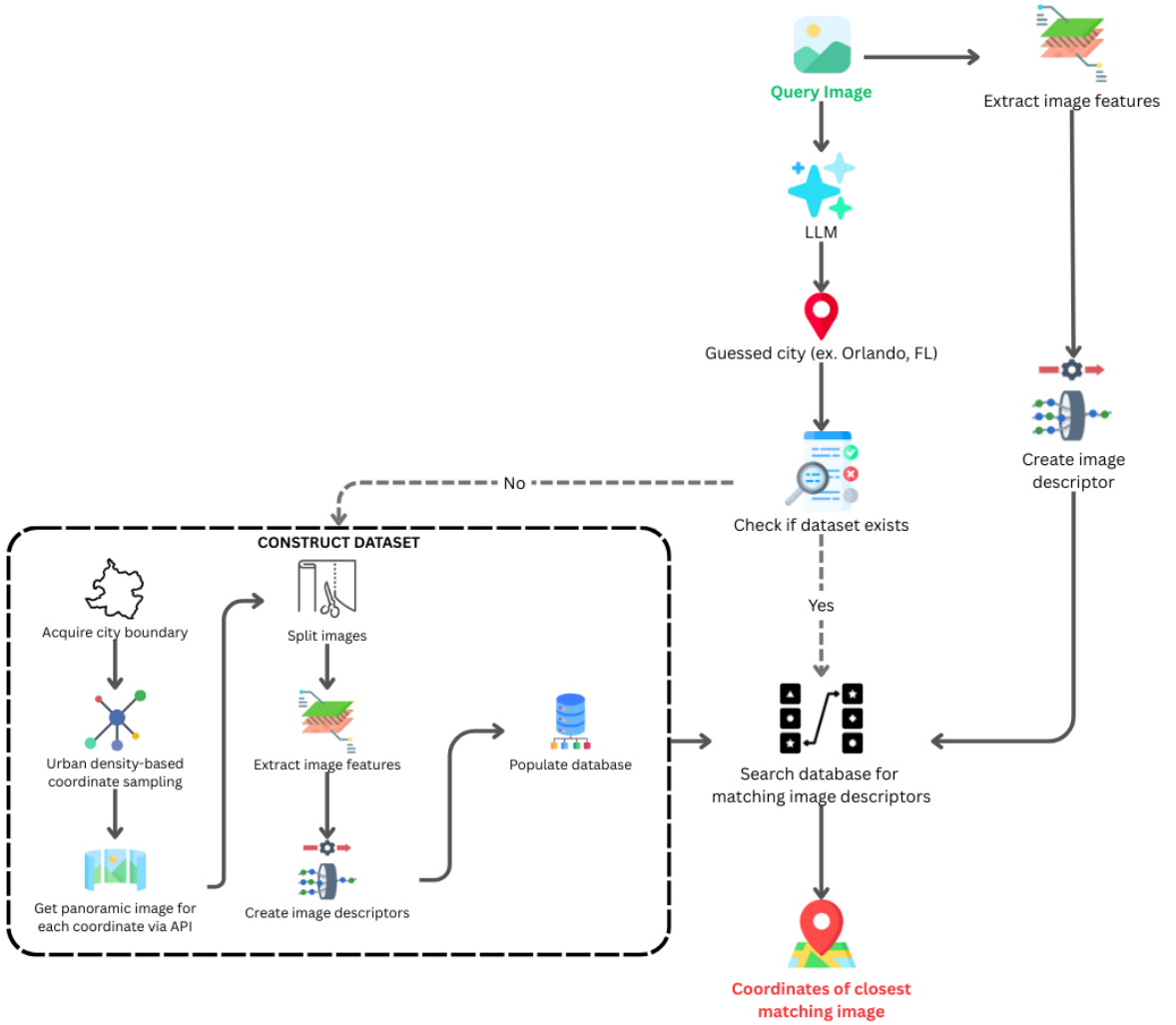
AI models correlate sidewalk width with pose-based behavioral metrics.

Our research reveals that street geometry significantly influences pedestrian behavior. Wider sidewalks promote greater exploration, offering valuable insights into human–vehicle interactions.

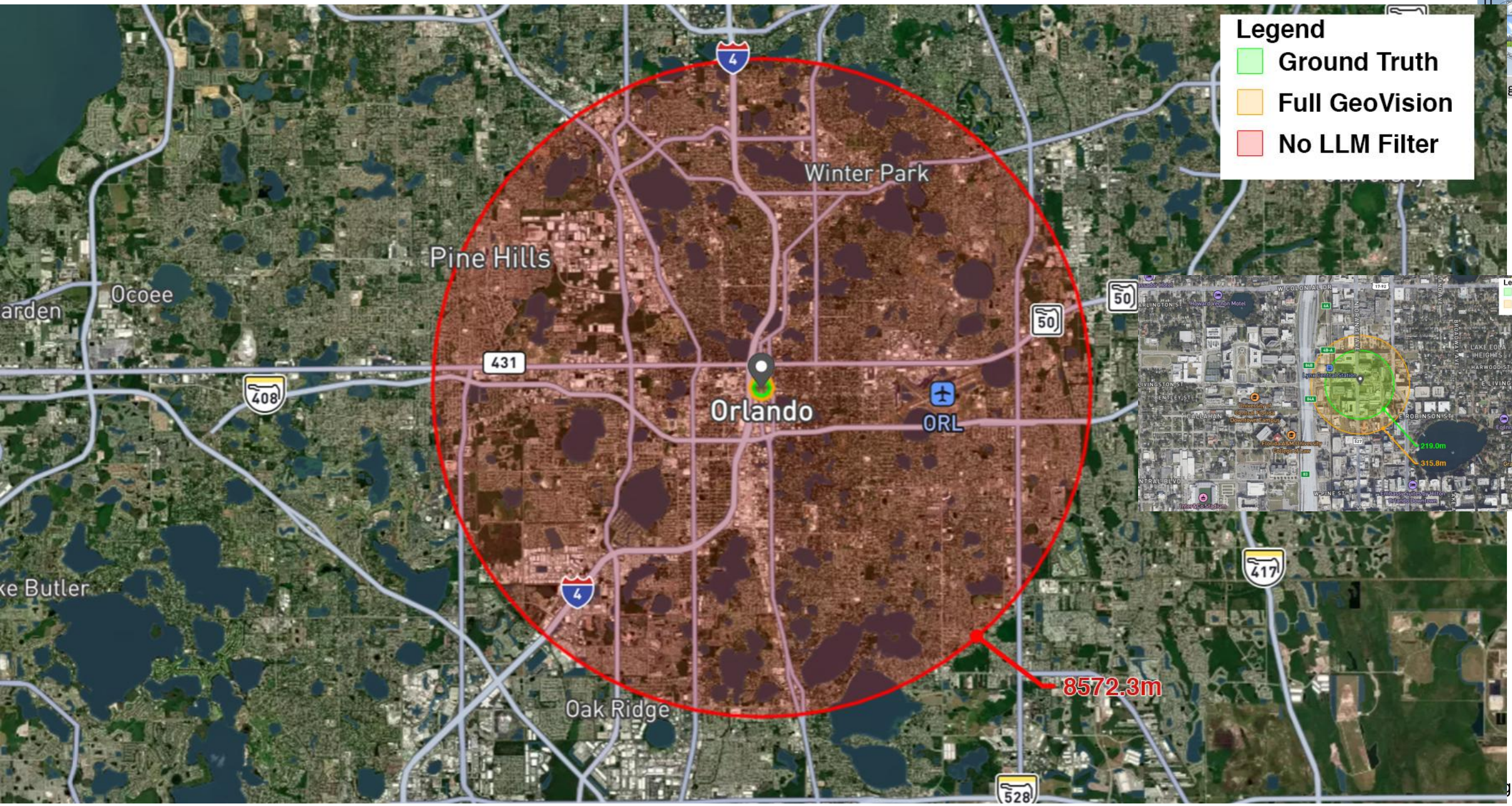

GeoVision

GeoVision Overview

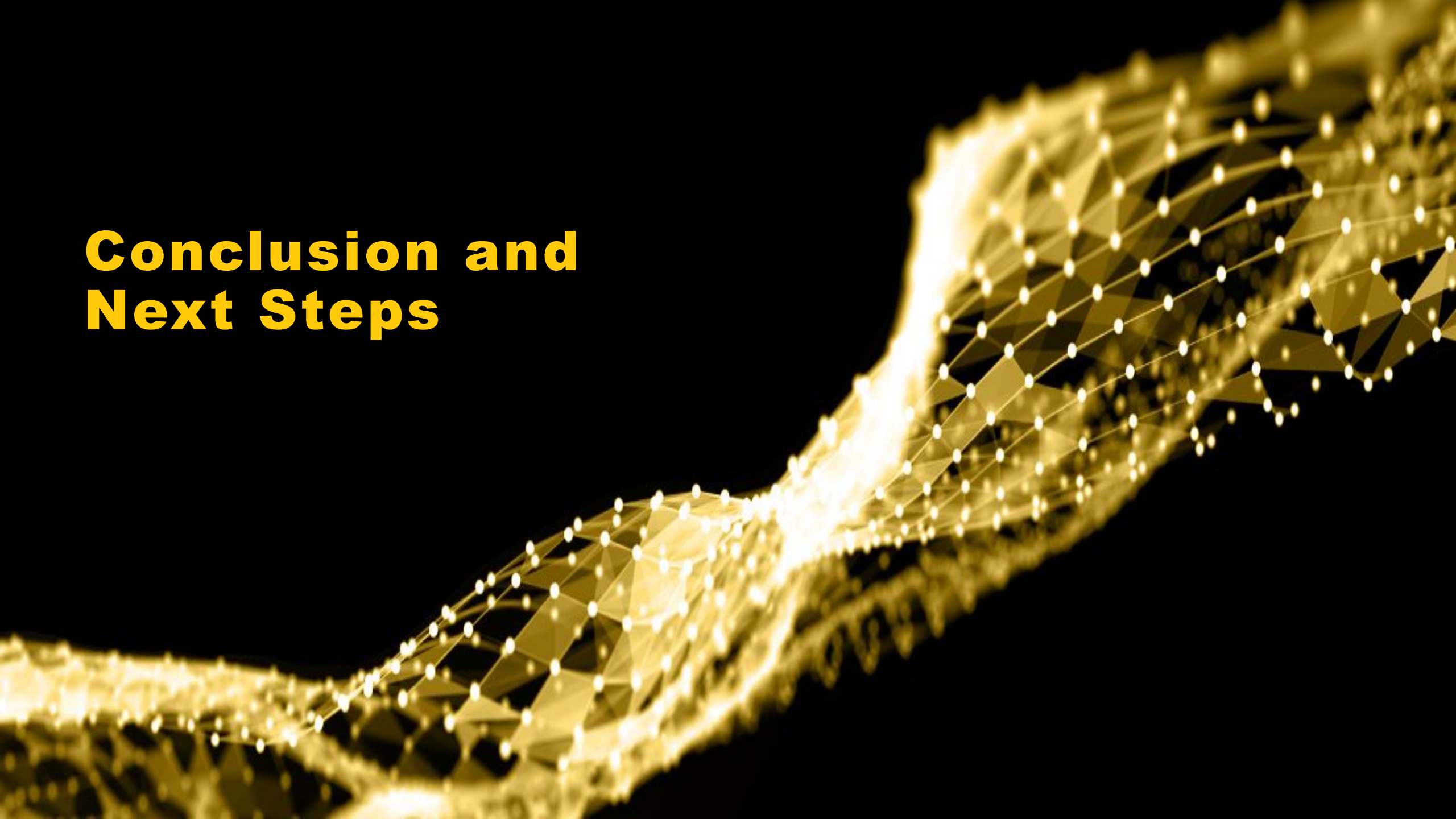
- GeoVision is a sophisticated image recognition system that performs visual geolocalization down to coordinate-level accuracy.
- It achieves this by using innate LLM knowledge to accurately guess the general location based on image analysis.
- Then cross-references that image against a dynamically-constructed dataset of georeferenced images for the guessed location.



Shervington, K., **Sabri, S.**, 2026. GeoVision: A Multi-Stage Visual Geolocalization System Using LLM and Feature-Based Image Matching.


Legend
Ground Truth
Full GeoVision
No LLM Filter
Winter Park
Pine Hills
Ocoee
Orlando
ORL
Oak Ridge
8572.3m
219.0m
315.8m

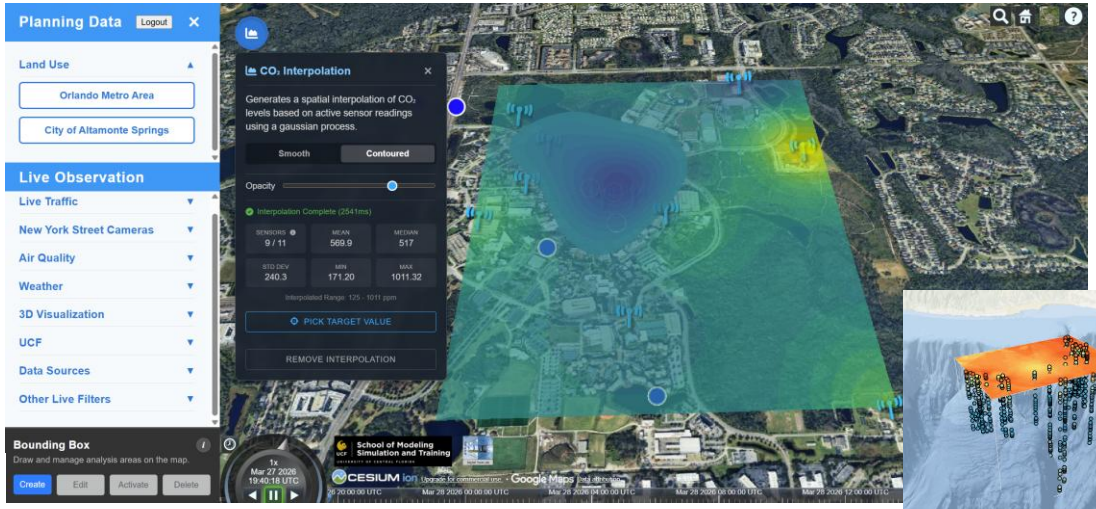
Conclusion and Next Steps



Spatially Explicit Urban Digital Twin

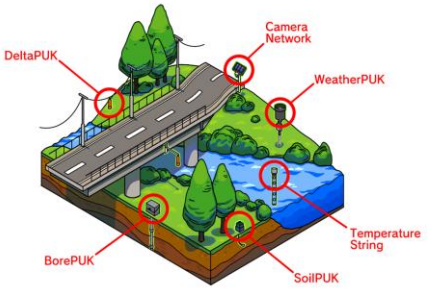
Digital Twin Lab

- Spatially explicit Digital Twins for Disaster Management (Disease, Flood, Pollution)
- Spatial Graph Data Models to improve real-time data analysis (Semantic + Geometrical)
- Validation Verification and Uncertainty Quantification (VVUQ)

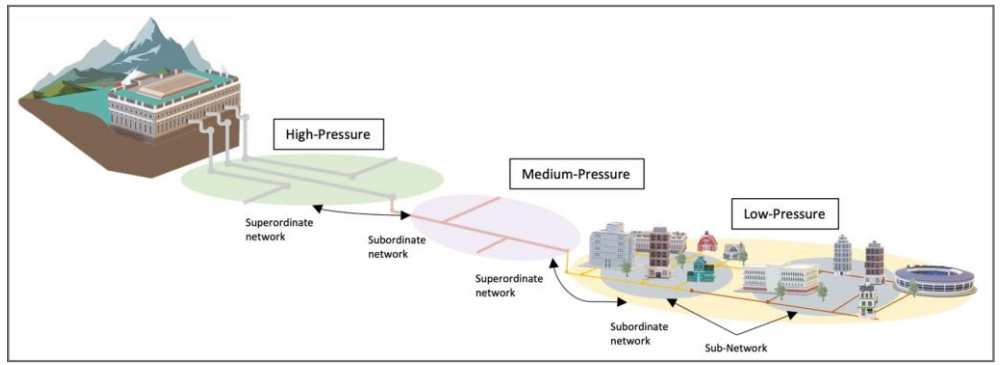


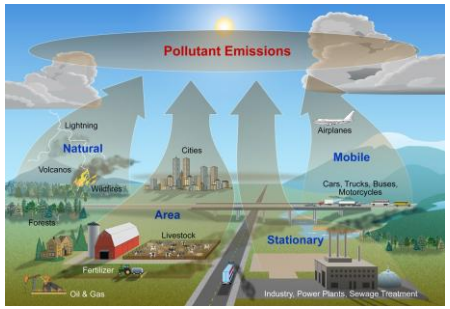
2D/3D

https://community.esri.com/t5/arcgis-geostatistical-analyst-blog/new-in-arcgis-pro-2-3-3d-interpolation-with/ba-p/883353



https://www.floodmapp.com/



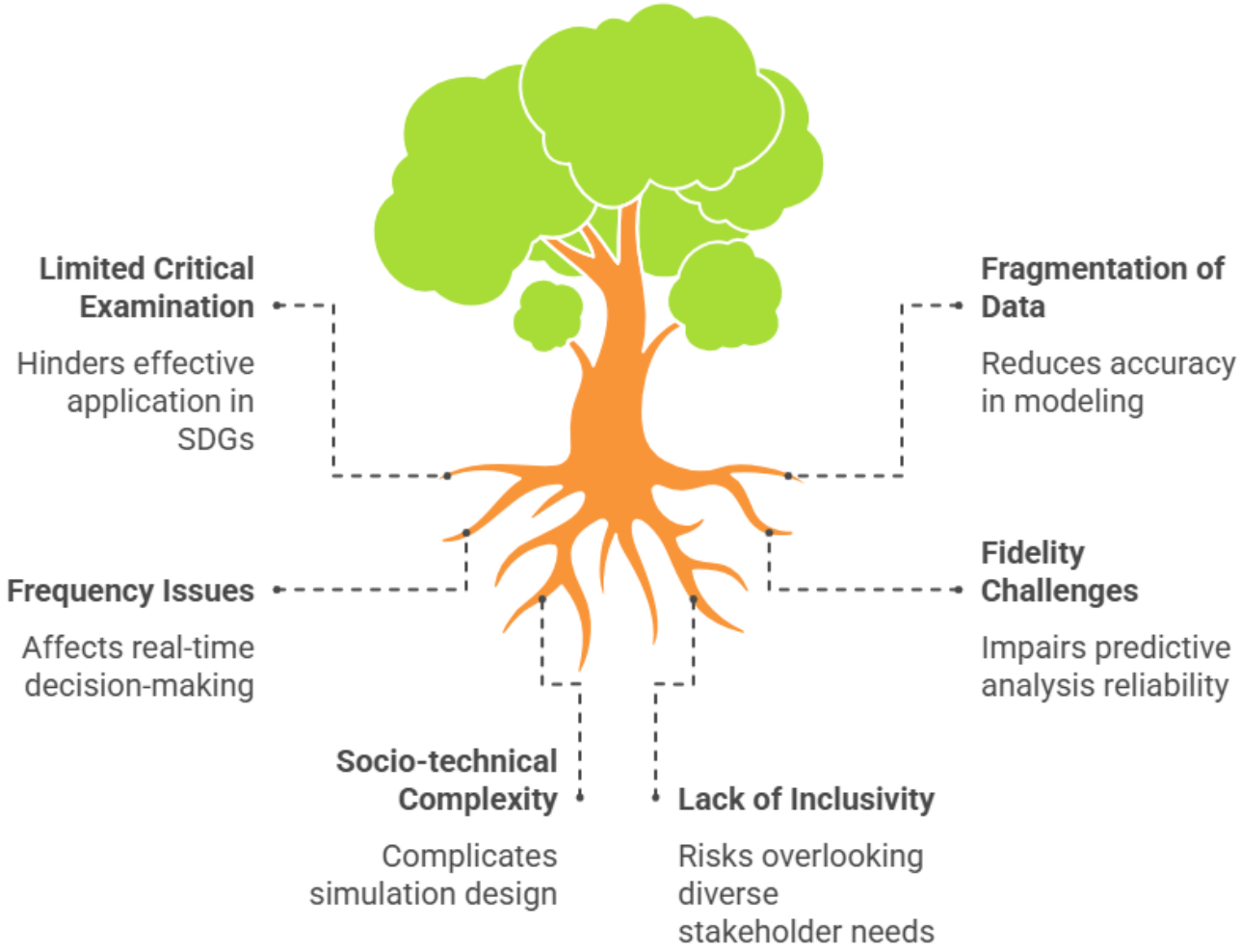


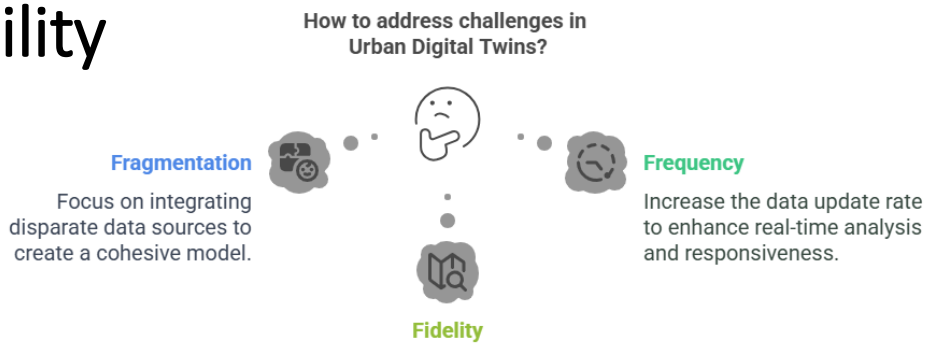
https://www.nps.gov/subjects/air/sources.htm

Javaherian Pour, E., Atazadeh, B., Rajabifard, A., & **Sabri, S.** (2025). Review and assessment of 3D spatial data models for managing underground utility networks. Tunnelling and Underground Space Technology, 157, 106219. https://doi.org/10.1016/j.tust.2024.106219

UCF

Challenges of GeoAI - Digital Twin in Sustainability

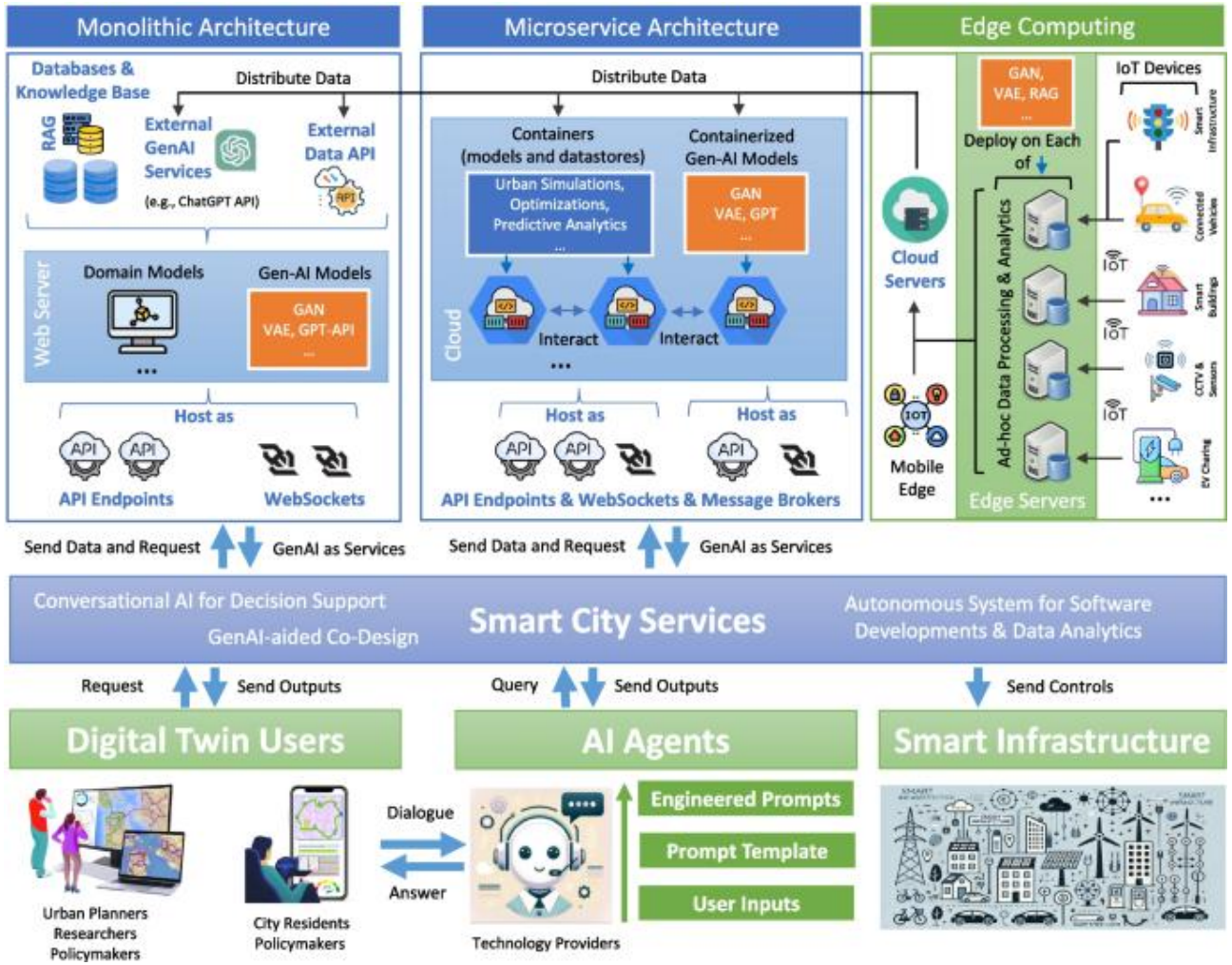


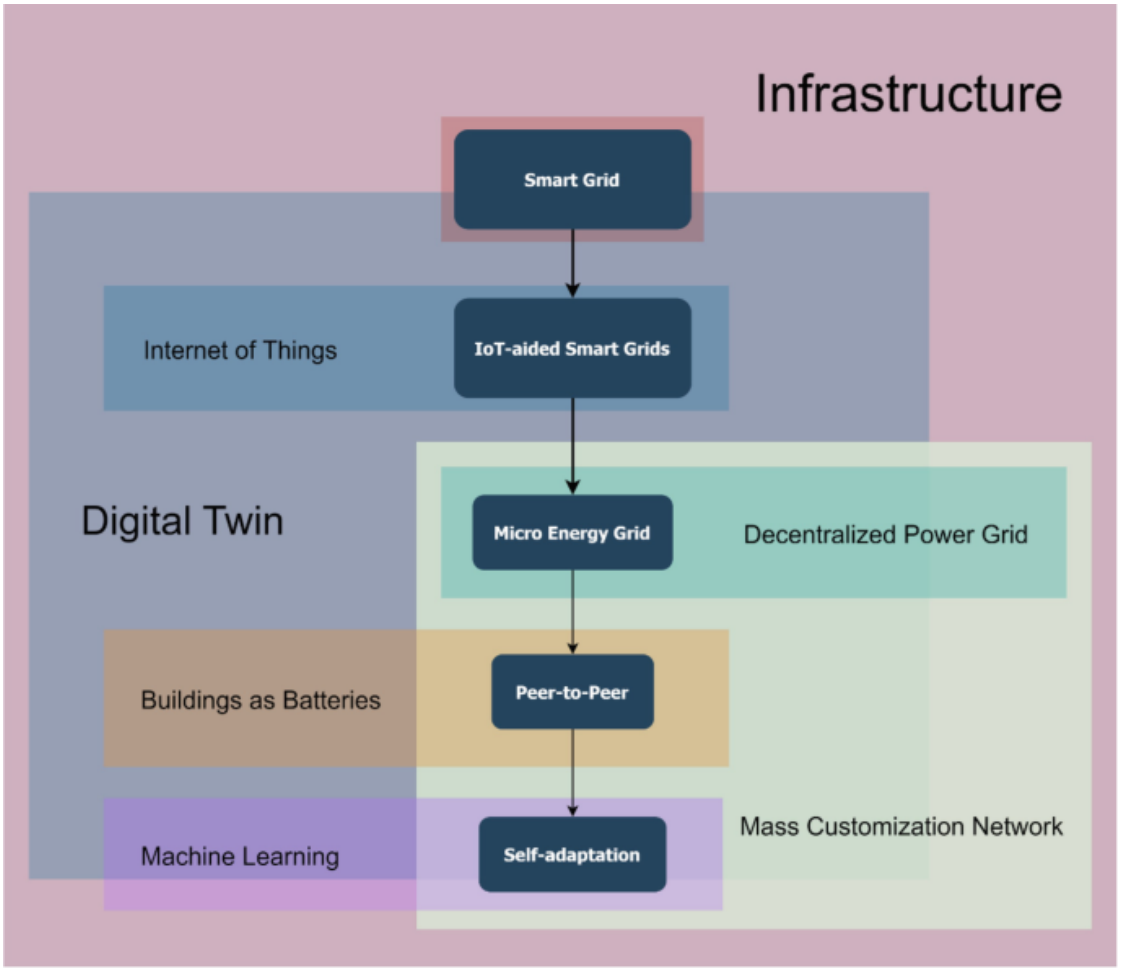


Tzachor, A., **Sabri, S.,** Richards, C. E., Rajabifard, A., & Acuto, M. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals. Nature Sustainability 2022, 1–8. https://doi.org/10.1038/s41893-022-00923-7

GeoAI Agents enabled Digital Twins for Smart City Advancements

Digital Twin Lab

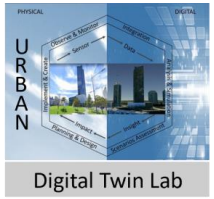




Xu, H., Omitaomu, F., **Sabri, S.** *et al.* Leveraging generative AI for urban digital twins: a scoping review on the autonomous generation of urban data, scenarios, designs, and 3D city models for smart city advancement. *Urban Info* **3**, 29 (2024). https://doi.org/10.1007/s44212-024-00060-w

Reynolds, J., **Sabri, S.**, Lee, B. (2024). Digital Twins for Creating Value Through "Buildings as Batteries" Using a Mass Customization Network. In: Sabri, S., Alexandridis, K., Lee, N. (eds) Digital Twin. Springer, Cham. https://doi.org/10.1007/978-3-031-67778-6_9

GeoAI Packages



- ***Scikit-learn*:** https://scikit-learn.org, consists of simple and efficient machine learning tools, including classification, regression, clustering, dimension reduction, data preprocessing and model evaluation metrics in Python.
- ***PyTorch*:** https://pytorch.org, a computational framework for building machine and deep learning models in Python.
- ***Tensorflow*:** https://www.tensorflow.org, another computational framework for building machine learning and deep learning models.
- **Keras:** https://keras.io, an effective high-level neural network Application Programming Interface(API) in Python and it is easy for most machine and deep learning beginners to learn and use.
- **Hugging Face:** https://huggingface.co, AI community that builds, trains, and deploys state of the art models(e.g., generative pre-trained transformers) powered by reference open-source in machine and deep learning.
- **GoogleEarthEngine:** https://earthengine.google.com, a multi-petabyte catalog of satellite imagery and geospatial datasets with planetary-scale analysis capabilities and the Earth Engine API for geocomputation and analysis is available in JavaScript and Python, e.g., the geemap package by Wu (2020).
- **ArcGISGeoAIToolbox:** https://pro.arcgis.com/en/pro-app/latest/tool-reference/geoai, contains ready-to-use tools for training and using machine/deep learning models that perform classification and regression on geospatial feature layers, imagery, tabular, and text datasets.
- **Opengeoai:** https://opengeoai.org/, offers a unified framework for processing satellite imagery, aerial photographs, and vector data using state-of-the-art deep learning models.

Thank You

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