# Forest Digital Twins as Specialized Spatial Digital Twins

## Zwillingstag der GDI-DE

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# Overview

# 1 Forests

# Forests

- Largest and most diverse ecosystems on Earth
- Trees defined by species composition, vertical structure, and horizontal distribution
- About 21% of the Earth’s land surface covered by forests
- About 3.04 trillion trees on the planet
- Terrestrial biodiversity
- +60,000 tree species providing habitat for 80% of amphibian species, 75% of bird species, and 68% of mammal species

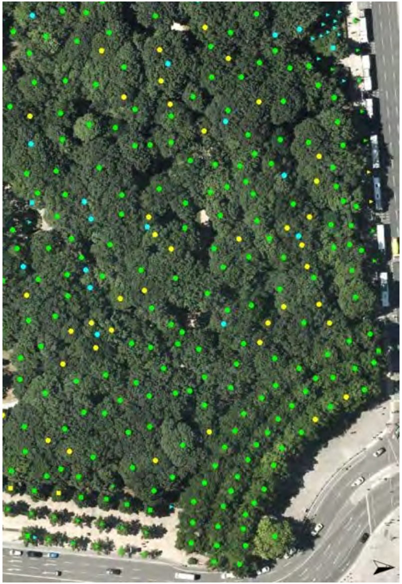
# Forests Ecosystem Services

- Provisioning services, e.g., timber production
- Regulating services, e.g., carbon sequestration, temperature regulation
- Cultural services, e.g., recreation and eduaction
- Ecosystem services, e.g., water cycles, nutrient cycles

- Trade-offs and synergies between different forest ecosystem services

# Urban Forests

- Trees and shrubs of a city, e.g., street, park, and yard trees
- Fragmented structure
- Special environmental conditions, e.g., heat island effect
- Intensive management, e.g., planting, irrigation, pruning
- Solutions for cooling air during heat waves, absorbing water during heavy rainfall, improving the quality of life etc.

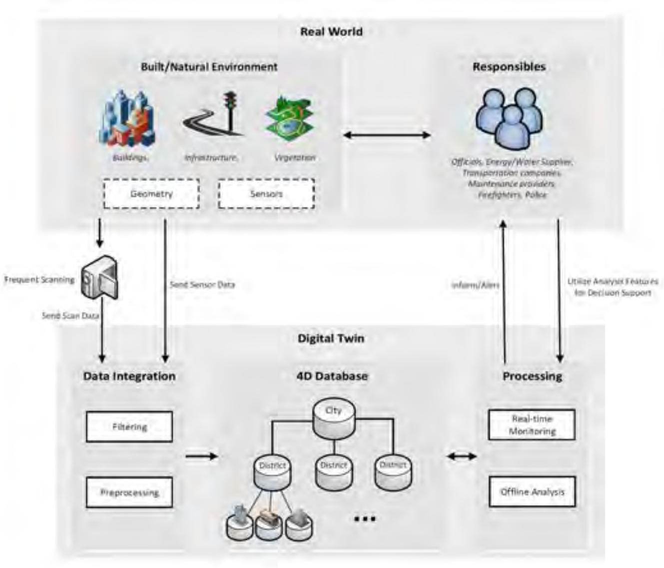


# 2 Digital Twins

# Digital Twins

## Characteristics

- Continuous Updating
- Multimodal, Heterogeneous Data Integration
- Temporal Synchronization
- Simulation Capabilities
- Bidirection Data Flow
- Interoperability



# Forest Digital Twins

## Digital Twins – Some Definitions

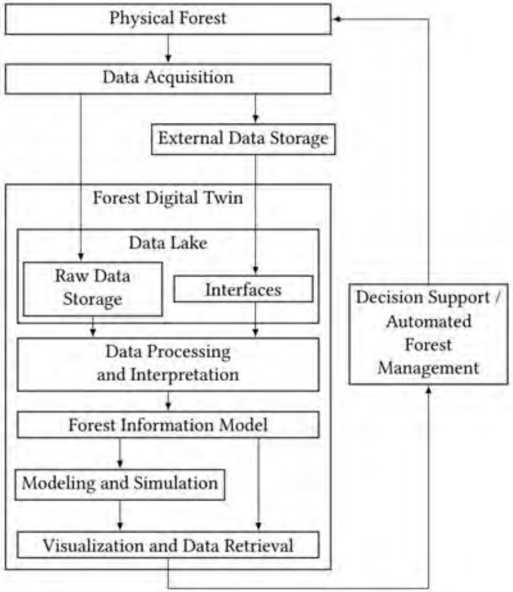
- *”Virtual representations of real-world objects or systems that are continuously updated by incoming data and can be used to monitor, predict, or even control the state of the real-world object”* → Real Objects, Systems, Processes
- *”The effortless integration of data between a physical and virtual machine in either direction”* → Bidirectionality
- *”A digital twin is a digital representation of a physical item or assembly using integrated simulations and service data. The digital representation holds information from multiple sources across the product lifecycle.”* → Relevance for the Whole Lifecycle
- *”This information is continuously updated and is visualized in a variety of ways to predict current and future conditions, in both design and operational environments, to enhance decision making”* → Prediction, Decision Making
- *”A DT is a living, intelligent and evolving model, being the virtual counterpart of a physical entity or process.”* → Integral Part

# 3 Forest Digital Twins

# Architecture

**Forest Digital Tree System**

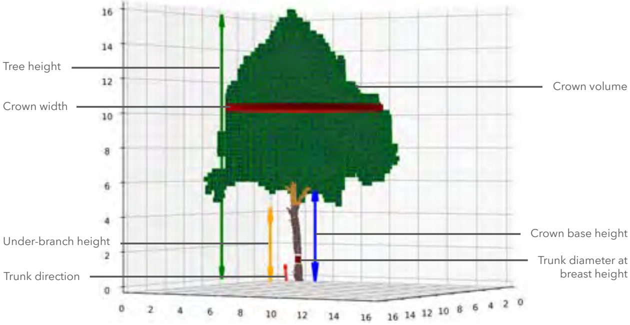
- Data lake for storing raw data
- Data stored by third-party data providers via interfaces
- Data processing methods to extract information from the raw data
- Forest information model: basis for modeling and simulation as well as for information visualization



# Architecture

**Tree Models and Attributes**

- Geolocation and terrain model
- Species
- Age
- Iso-density curves for roots
- Cylinder models to represent branches
- Crown estimation and representation



# 4 Data for Spatial Digital Twins

# General Data Sources

- GIS Data
- LiDAR Sensors
- Radar Sensors
- GPR Sensors
- Imaging Sensors

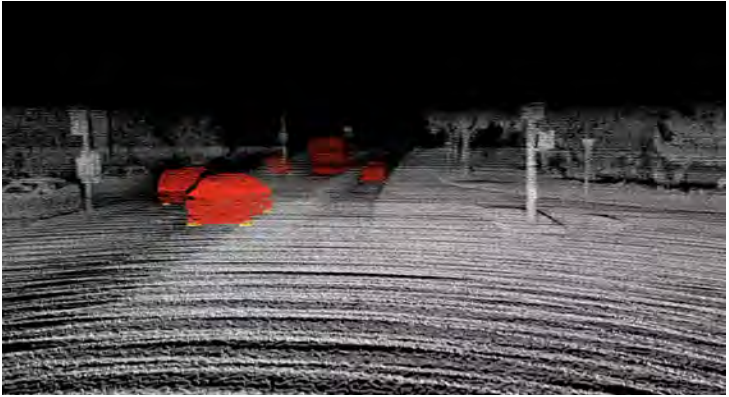


Figure: Example: 4D ”LiDAR-on-Chip” (https://www.aeva.com/aeries-ii/).

# General Data Sources

- AI-equipped sensors
- Bio Environment sensors
- Chemical sensors
- Micro sensor networks
- Terahertz sensors
- Living sensors

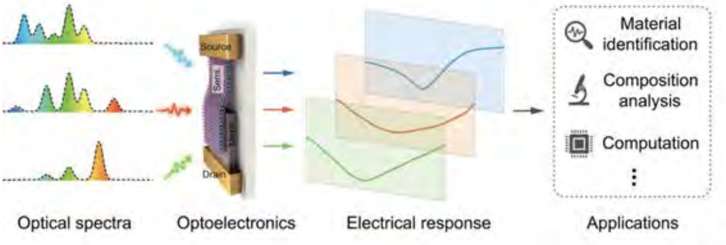
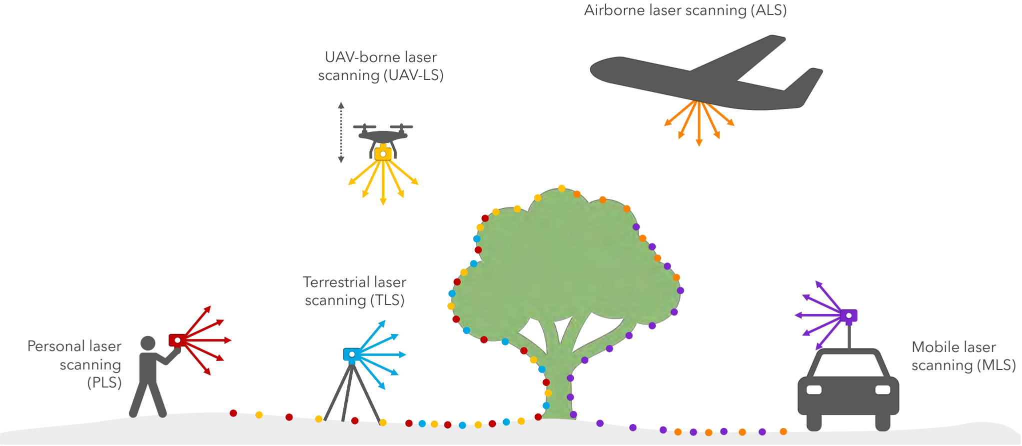



Figure: Example: Miniaturized spectral sensing with a tunable optoelectronic interface (Xiaoqi Cu et al., 2025).

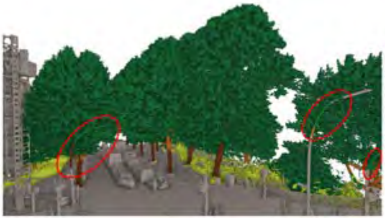
# Data Acquisition for Forests

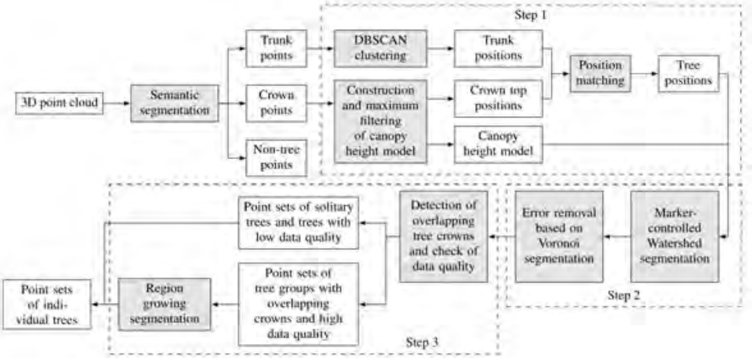


# Data Acquisition - Tree Delineation

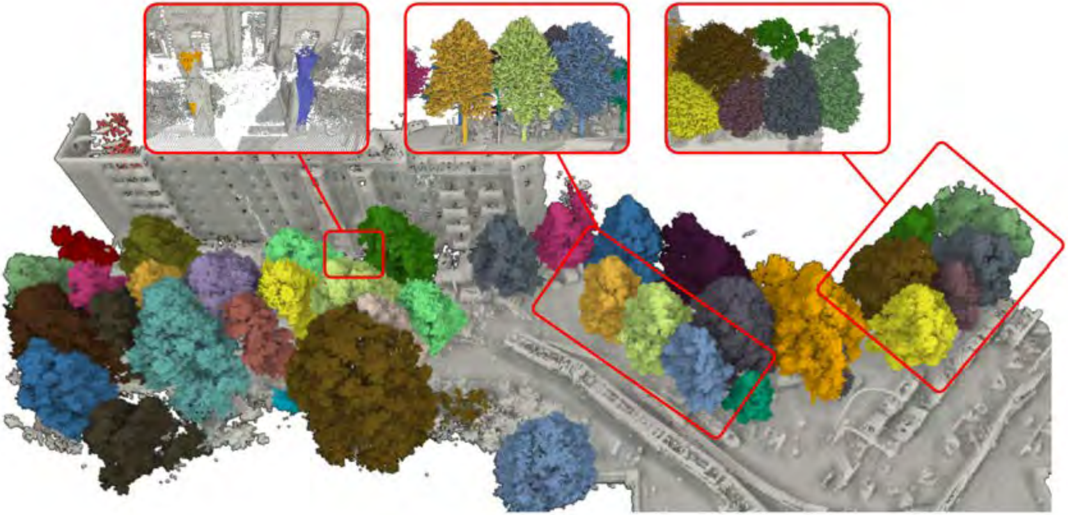
## Challenges

- Intrinsic complexity of natural objects
- Finding core components of a tree
- Hybrid approach for segmenting tree point clouds (e.g., coarse-to-fine segmentation (HPI))



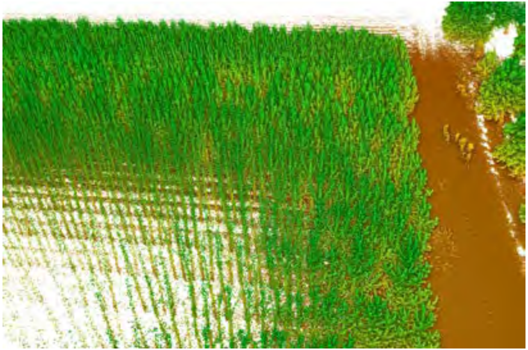


# Data Acquisition - Tree Delineation



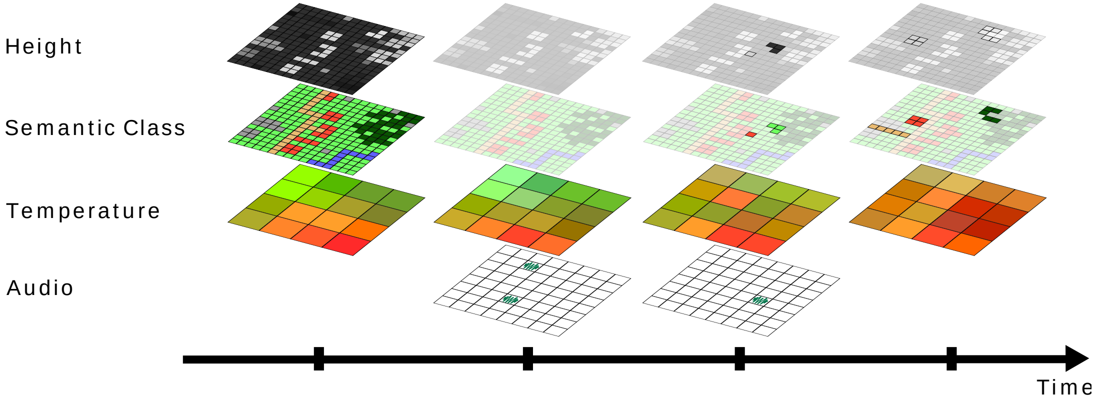
# Data Management Challenges

- Orchestration of diverse data collection processes
- Technical logistics (e.g., maintenance of IoT devices)
- Data transmission and storage (e.g., low-power wireless transmission)
- Different spatial and temporal scales
- Combination of ground-based, airborne, and spaceborne data acquisition approaches



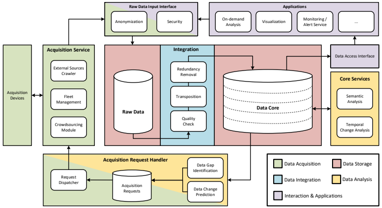
# Data Management Challenges

Work in Progress: Deep Learning on Mixed, High-Dimensional Georeferenced Data

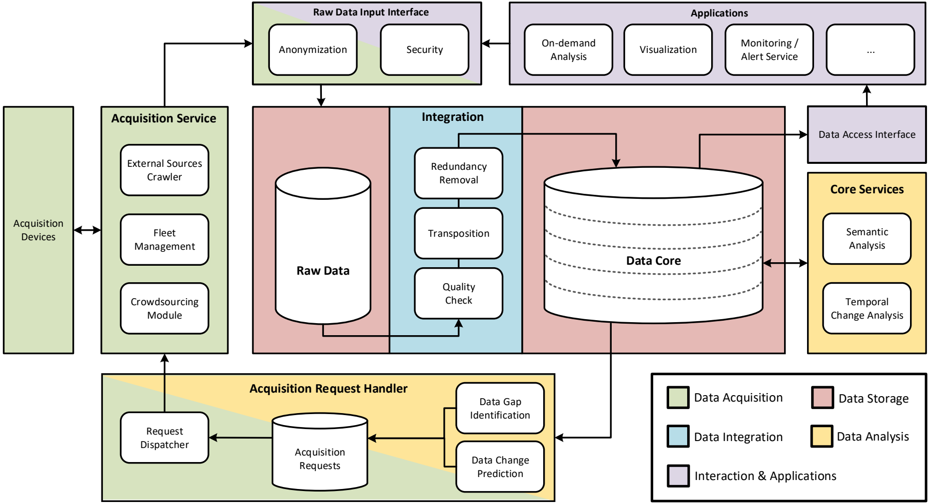


# Data Lakes

- Central repository storing large volumes of structured, semi-structured, and unstructured data
- Examples: streamed sensor data and 3D point cloud data
- Processing, analysis and modeling methods may improve over time
- New functionality for new applications and research questions
- Key challenge: massiveness of the data, heterogeneous data, different spatial and temporal scales



# Data Lakes



Raw Data Input Interface
Anonymization
Security
Applications
On-demand Analysis
Visualization
Monitoring / Alert Service
...
Acquisition Devices
Acquisition Service
External Sources Crawler
Fleet Management
Crowdsourcing Module
Integration
Redundancy Removal
Transposition
Quality Check
Raw Data
Data Core
Data Access Interface
Core Services
Semantic Analysis
Temporal Change Analysis
Acquisition Request Handler
Request Dispatcher
Acquisition Requests
Data Gap Identification
Data Change Prediction
Data Acquisition
Data Storage
Data Integration
Data Analysis
Interaction & Applications

# 5 Data Visualization for Spatial Digital Twins

# Visualization of Tree Data

- Facilitate exploration and interpretation of complex datasets
- Visual analytics to support informed decisions
- Abstract information visualization for analytics
- High-fidelity visualization

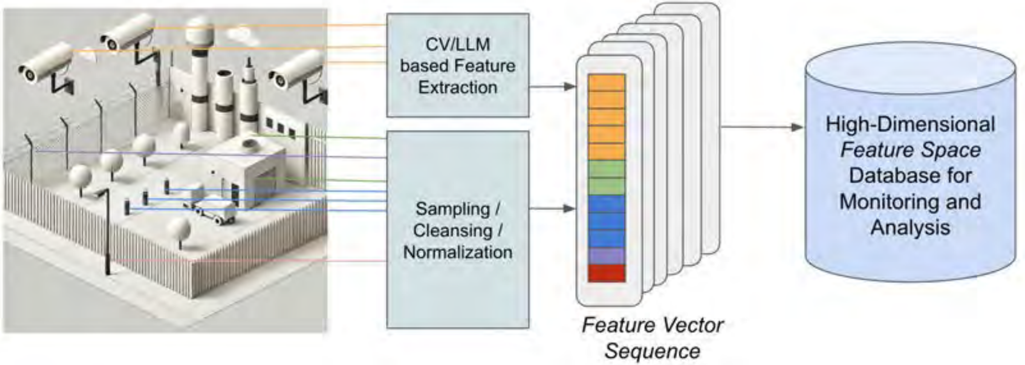
- Example: Nonphotorealistic rendering of classified 3D pointclouds

# Visualization of 3D Pointclouds

Example: Non-Photorealisic Rendering of 3D Pointclouds

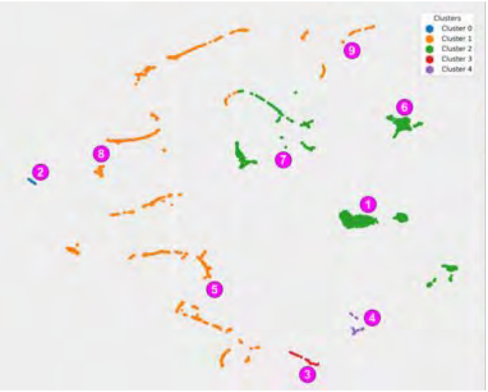
# Visualization of Feature Vectors

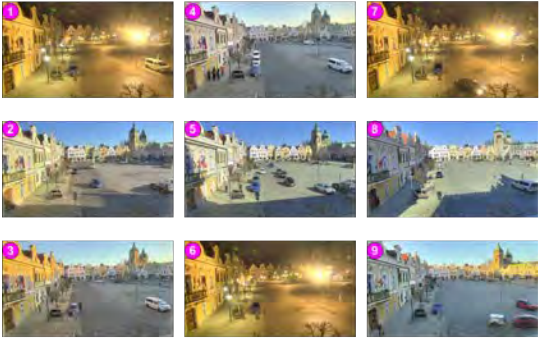
- Feature vectors encode characteristics of a spatial site, e.g., detected objects, physical parameters, etc.
- Feature vectors are high dimensional, generated a high frequency
- A single feature vector has no concrete meaning



# Visualization of Feature Vectors

- Clustering is computed in the high dimensional space
- Visualization is based on dimensionality reduction
- Cluster are assigned application specific meanings
- Segments of time series vectors are semantically related to the clusters they are close to



# 6 Conclusions

# Conclusions

**Spatial Digital Twins**

- One key requirement for spatial digital twins are *steady, reliable and automated input data streams*.
- The *automated, AI-based segmentation and classification of 3D point clouds* enables us to derive semantically meaningful objects and structures specific to the application context (e.g., forests).
- *Bidirectional connectivity* is the key to new applications, such as real-time detection of critical events and processes in spatial environments.
- The *integration of heterogeneous and georeferenced sensor data with spatial data* is usually necessary to enable bidirectionality in operational processes.
- To this end, *high-dimensional feature vectors* that reflect snapshots of spatial locations enable the interpretation and understanding of structures, processes, and dynamics in spatial environments.

Digital twins lead to cyber-physical systems, in which the digital twin becomes part of the original system and *merges with it* in the long run.

# Contact

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