Spatial Digital Twins and Spatial Consciousness – Key Technologies for the Next Generation of Industry 4.0

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Introduction

Sirius focuses on AI-based technology for *industrial and urban spatial environments* at various scales, from manufacturing plants and factory environments to infrastructure-intensive facilities and urban areas. What they all have in common is that their complexity is growing exponentially, not only due to new technological innovations, but also due to an increasing variety of interactions and interdependencies.

At a time when Artificial Intelligence, Metaverse, VR/AR, IoT and Big Data are fundamentally changing our world, Sirius is at the forefront of leveraging these technologies for technical environments in the form of the next generation of Industry 4.0 based on *spatial digital twins* and a radical new AI-based concept called *spatial consciousness* to enable and ensure highly efficient, highly automated processes in technical environments, including automated material handling, smart manufacturing cells, traffic information, predictive maintenance, energy efficiency and effective human-machine collaboration.

These approaches can become almost invisible once they are seamlessly integrated into everyday life. In the scope of mobility and transportation (Fig. 1), for example, “Digital twins can contribute to making transportation systems more dependable, convenient, and sustainable by enhancing efficiency, safety, and planning. Their ability to model, analyze, and predict various aspects of transportation infrastructure and operations leads to improved efficiency, reduced costs, enhanced safety, and ultimately a more sustainable and seamless transportation experience for individuals and goods alike.” [1]

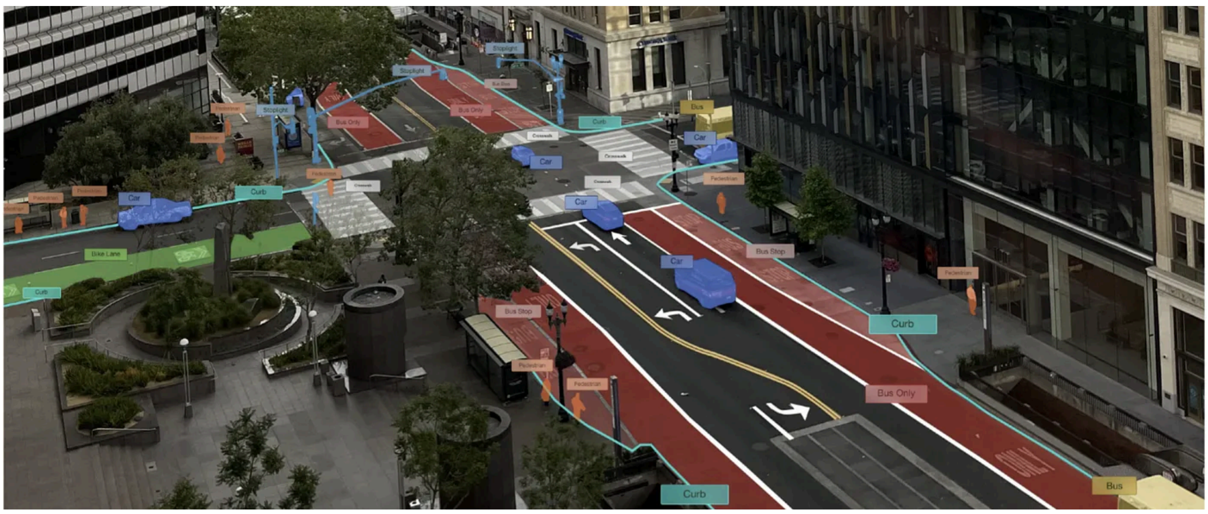

Figure 1: Illustration: Spatial digital twins for transportation and mobility (Source: [1])

Industrial and Urban Spatial Environments

We humans perceive industrial and urban spatial environments at different scales - at the micro level, close to our hands, at the meso level, e.g. indoors, and at the macro level in the form of plants, sites and factory premises. A characteristic of this type of physical space is that it hosts a variety of activities and involves different human and non-human actors. It is a *shared, multifunctional space* subject to physical, technical, biological, social and legal constraints, synergies and conflicts.

A wide range of technologies (e.g., near and remote sensing, Fig. 2) allows us to capture and process data about different geometric, physical and structural aspects of the environment, its objects and the processes taking place in it. We can draw on models, data and ontologies based on a wealth of expertise. Remote sensing, such as LiDAR or image-based photogrammetric approaches, allows us to capture the geometry of an environment in real time using 3D point clouds - a universal, generic 3D representation that can be post-processed through deep learning analysis.

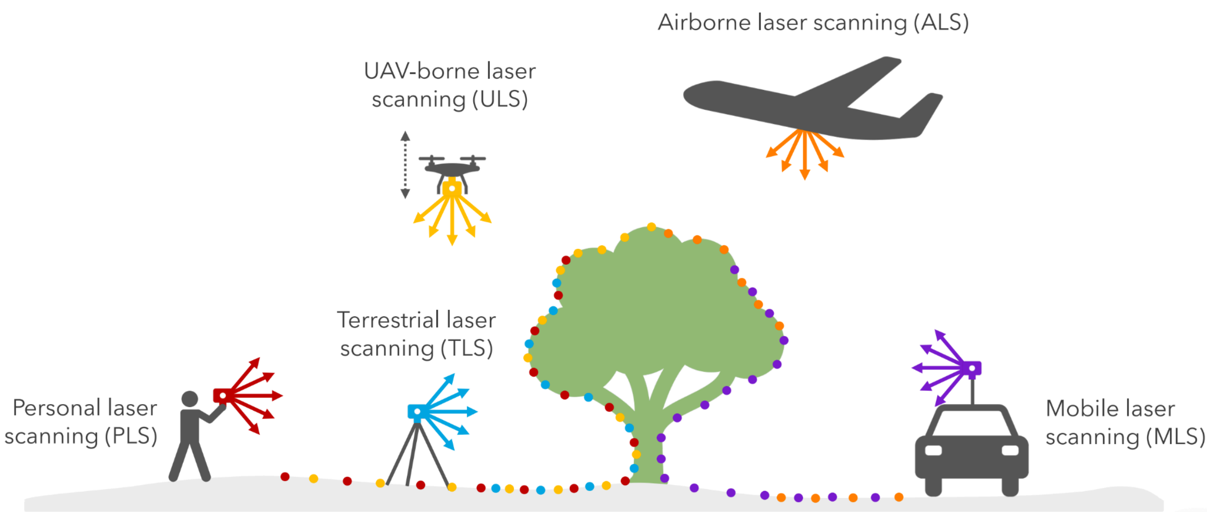

Figure 2: Example of capturing an environment by 3D point clouds by different sensing technologies at different scales [2].

A key challenge for the next generation of Industry 4.0 applications and systems is to couple such environments with spatial digital twins and embed the highest level of artificial intelligence, evaluation and self-reflection capabilities, i.e. a kind of spatial awareness. The end result is a *hybrid space* that seamlessly connects physical and digital space. Especially for industrial and urban environments with a high degree of structural complexity, new possibilities arise for the characterization, optimization and control of these *complex systems*.

In production lines, factories, laboratories, or inner-city hotspots, processes and events typically unfold on *multiple and interwoven spatial and temporal scales* whose structure and behavior cannot be easily described. For example, the way people physically move in a spatial environment over time is beyond human intuition, but can be revealed through geospatial analysis and information visualization (Fig. 3). In addition, there are always networked systems in sites that overlap, interact, or are layered. They are also a valuable source of sensor and environmental information. AI, and especially geospatial AI [3], allows us to access and extract a wide range of semantic information from a heterogeneous sensor data pool.

Figure 3: GPS-tracked pizza delivery routes in Manhattan over the course of a night. This spatio-temporal dataset allows us to uncover a number of mobility, sociological, and economic issues. (E.D.W. Lynch, 2012).

In manufacturing, for example, each component must meet defined quality and safety standards; inspection processes, such as those for component surfaces, must be performed with objective precision and high process reliability. With a spatial digital twin of the production lines, an intelligent data platform, and a variety of IoT modules for digitizing inspection processes and shop floor management, the risk of production errors can be drastically minimized and any errors can be tracked along the value chain for all manufactured components.

Industrial and urban spatial environments are also “living spaces” and as such they must be designed to meet the needs of the people who work and live there in order to be efficient and successful. A human-centered approach is therefore always key as future growth and sustainability will increasingly depend on a balance between economic, technical and social interests. To this end, spatial consciousness and spatial digital twins provide a vision and approach to achieve these goals.

Components of Spatial Digital Twins and Spatial Consciousness

Sirius solutions combine and extend a number of key IT technologies to implement spatial digital twins and spatial consciousness technologies such as:

- On-site remote sensing with integrated AI-based computer vision
- IoT to control, manage, and connect intelligent components and devices
- Real-time creation of high-dimensional feature vectors as information distillates
- Deep Learning on high-dimensional feature spaces
- Visual computing [4] including computer vision and computational geometry
- Large language models (LLMs) to link and interpret data
- Explorative big data analysis and information visualization.

This combination results in a technology toolbox that Sirius can use to build a broad range of specialized spatial IT solutions of the next decade—making spatial digital twins, geospatial AI and spatial consciousness a reality.

Spatial Consciousness as Unique Feature

Spatial Consciousness arises when highly accurate, up-to-date and holistic information about a spatial environment and its objects and processes is continuously collected, fused, analyzed and evaluated. This includes maintaining and updating a comprehensive knowledge base of static and dynamic states, processes and events, which are derived from distilled information that can be directly used by deep learning technology. What thus characterizes Spatial Consciousness is the *holistic long-term memory* that enables these systems to make statements about the spatial environment and to classify and evaluate objects and processes. This functionality provides a robust framework for complex analysis and enables the validation or refutation of hypotheses in relation to interlinked phenomena. Rather than remaining a black box, AI becomes transparent through tailored information visualization that complements spatial consciousness systems.

High-Dimensional Information Base

The algorithmic core of the Sirius technology is based on the continuous and automated acquisition and fusion of spatial and spatial-related data and the subsequent generation of an information distillate. This creates a knowledge and information base of the respective spatial environment in the form of high-dimensional feature vectors. The associated *high-dimensional feature space* forms the working basis for AI algorithms and large language models. Processes, phenomena or events can be evaluated currently, examined retrospectively and predicted for the future. Events and states can be classified and assigned to clusters, thus laying the foundation for the implementation and operation of powerful analysis and evaluation functions for applications and services.

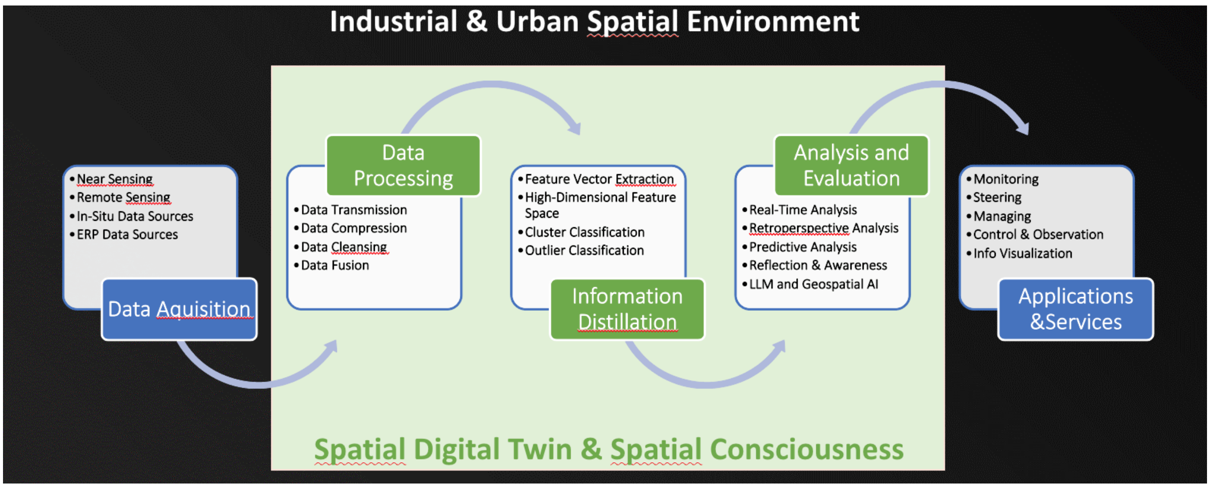

Figure 4: Working principle of spatial digital twins and spatial consciousness systems.

Example: Smart Parking Intelligence for Urban Optimization

Parking is a complex technical, physical, legal and emotional issue. Increasing traffic volumes combined with a shortage of parking spaces pose difficult challenges for politics, administration, business and society in this regard. Local authorities in particular are looking for ways to solve the imbalance between the limited supply of parking spaces and the ever-increasing demand for parking. For an intelligent solution, it is important to first analyze the actual usage of an environment, derive the underlying needs and requirements from the collected data and then dynamically control, direct and monitor the parking situation and inform drivers accordingly.

Conventional sensor-based parking guidance systems face problems in terms of scaling and pragmatics due to their focus on individual parking spaces. In contrast, the 'Smart Parking Intelligence for Urban Optimization' project relies on intelligent cameras with state-of-the-art edge computing functions. With the help of spatial awareness technology, not only the occupancy of parking spaces, but also the entire traffic and parking situation, including the surrounding, visibility and weather conditions, can be continuously recorded and evaluated by cameras, e.g., parking in second rows or in restricted areas. On-edge calculation of traffic and parking events means that only encrypted feature vectors are sent to a central data hub, ensuring compliance with strict data protection regulations, especially in public spaces.

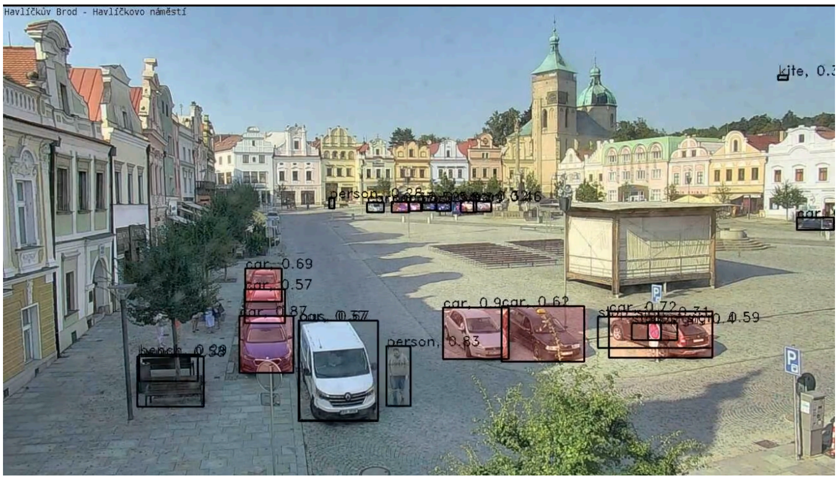

Figure 5: Camera view of a corner of the marketplace, capturing various aspects of mobility, such as people, their movement, and the inventory of the place (VIVALDI parking solution).

Vision Becomes Reality

Our vision for Industry 4.0 and spatial digital twins for industrial and urban spatial environments is gradually being translated into powerful and reliable technical systems. They are characterized by the fact that the collected, heterogeneous, fused data accurately captures spatial environments, learns from them and *develops an understanding* of what is happening over time. Sirius is turning this vision into real, highly reliable systems today.

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