Intelligent Road Intersections: A Case for Digital Twins

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Abstract. *Smart cities are based on complex systems that use legacy infrastructure and modern and intelligent solutions to achieve a highly efficient functioning of society in several verticals. In the context of road intersections, the main objective is to offer safe, efficient, and reliable mobility services for all agents involved in the physical space (infrastructure, vehicles, and pedestrians). The digital twin paradigm has recently been considered by both academia and industry as a means for reaching intelligent transportation solutions. The article makes a case for digital twins in intelligent intersection modeling as it is expected to consolidate real-time monitoring, control, and management of intelligent intersections. The design of a framework and the development of a testbed are presented in this paper. New functionalities for the safe operation of the road intersection are the expected results of this proposal.*

Resumo. *As cidades são baseadas em sistemas complexos que usam infraestruturas legadas e soluções modernas e inteligentes para alcançar um funcionamento altamente eficiente da sociedade. No contexto das interseções rodoviárias, o principal objetivo é oferecer serviços de mobilidade seguros, eficientes e confiáveis para todos os agentes envolvidos no espaço físico (infraestrutura, veículos e pedestres). O paradigma do gêmeo digital tem sido recentemente considerado, tanto pela academia quanto pelas empresas, um meio para alcançar soluções de transporte inteligentes. Este artigo faz uma defesa dos gêmeos digitais como arcabouço de cruzamentos inteligentes de forma a consolidar o monitoramento, o controle e a da sua gestão em tempo real. O projeto de um arcabouço e o desenvolvimento de um testbed são apresentados neste artigo. Novas funcionalidades para o funcionamento seguro do cruzamento rodoviário são os resultados esperados desta proposta.*

1. Introduction

The development of digital systems, communication systems, and computer systems has allowed for some time to bet on a new concept of a modern city. The smart and digital cities propose a complex system that, through the use of basic infrastructures and intelligent solutions, will allow a highly efficient functioning of society in several verticals such as transport, health, and energy [Deka et al. 2018]. Reliable and high-performance communication systems and the development of management and control applications in different domains that demand great computational power are some of the main technical challenges of this new city paradigm. Furthermore, new solutions must be able to contribute to the economic development and environmental sustainability of cities, ensuring competitiveness, safety, innovation, and social cohesion in order to improve the quality of life of its residents and increase the performance of the different business models [Okai et al. 2018].

In this context, transport cyber-physical systems (TCPS) allow transport systems to achieve high efficiency and reliability by interacting with cybernetic systems and physical transport systems. These systems can be the most critical and distributed infrastructure systems, making their implementation more challenging in today's cities. Given the complex integration of heterogeneous elements that include, such systems require a careful design through service-oriented architectures that provide scalability, flexibility, and security in their management and subsequent control [Kant 2016].

The development of emerging services for city road intersections has gained significant space. Intelligent intersections emerge as a real-time service between infrastructure, vehicles, and non-vehicles that intervene in transport systems to achieve efficient and safe operations at conflict intersections. Such solutions require efficient context detection systems supported by vehicle-to-everything (V2X) communications to interact with local and remote traffic controllers. In addition, there is a growing interest in non-signalized intersections control, using intelligent roadside units [Budan et al. 2018] as a way of mitigating the bottlenecks that traffic light systems represent. Furthermore, vehicle safety solutions for road accident prevention are being addressed as a critical factor in current intelligent transportation systems.

Emerging technologies are being adopted to implement intelligent transportation systems to achieve flexible, robust, and reliable solutions. In addition to the use of modern internet of things architectures, 5G communication systems, and multi-access edge computing platforms at the edge, digital twins have recently gained popularity among academia and industry for intelligent transport solutions [Bao et al. 2021]. This paper addresses the use of digital twins in intelligent intersection modeling for real-time monitoring, control, and management. A framework is proposed to develop the digital twins of road intersections and the applications and services that run on top. To the best of our knowledge, this paper is the first proposal to utilize digital twins to model road intersections and develop safety applications on top of such a model. The proposal is part of research under development at the Federal University of Espírito Santo in collaboration with local companies in the sector.

2. The Digital Twin Paradigm

The first attempt to formalize the digital twin concept was proposed by Michael Grieves as part of a product lifecycle management system [Grieves and Vickers 2017]. The proposal defined the main elements of a digital twin model: the physical element, its representation in the virtual space, and the data and information connections that connect the virtual and physical worlds. However, this first approximation only represented a starting point from which different approaches were proposed, based on the nature of the problems solved [Semeraro et al. 2021].

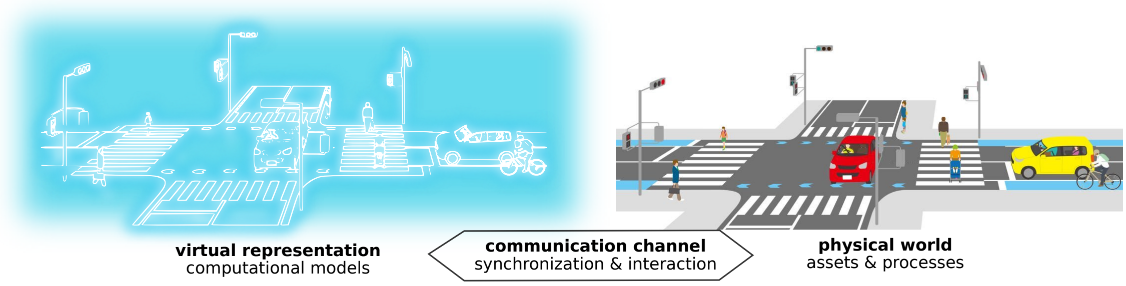

Figure 1. Digital Twin Paradigm.

The absence of an overall standardized architecture for digital twins makes their adoption and implementation slow. Moreover, their reproducibility and reuse become nearly impossible when it crosses the boundaries of a specific solution. With these limitations insight, the Digital Twin Consortium [1] emerged in 2020, a conglomerate of industry, academia, and governments, to accelerate the development, adoption, interoperability, and security of digital twins and their enabling technologies. The consortium formally defined digital twins as *"a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity"*, that will allow transforming business models through understanding, optimal decision-making, and effective action, using real-time and historical data to represent the past and present and simulate predicted futures.

Figure 1 shows the conceptual representation of digital twins: i) the physical assets, entities that conceptually have a specific objective in the real world and interact with other assets to form systems in the physical environment, implemented through different processes; ii) the virtual representation of the physical space, containing representational models based on structured information that represents the states of physical entities and processes, and computational simulation models that execute models using data and algorithms based on the information obtained by the representational models; and iii) a bidirectional, reliable and low-latency communication channel that enables the mechanisms of synchronization and interaction of real-world entities and processes with their digital twin.

3. Our Proposal: A Framework for Digital Twins in Intelligent Road Intersections

Digital Twins for intelligent transportation systems and specifically for intelligent intersection solutions can be defined as the digital representation of the intersection components, including i) the intelligent infrastructure (roads, traffic lights, and roadside elements in general), ii) the traffic participants (vehicles, non-vehicles, pedestrians, etc.), iii) the traffic behavior (departure, destination, path, etc.), and iv) the surrounding environment (urban functional area, weather condition, etc.). A successful representation and reliable virtual models significantly improve common problems of the crossings, even with the early discovery of such problems. Thus, short, medium, and long-term strategies can be designed to support decision-making at intersections, transforming them into safer scenarios.

[1]https://www.digitaltwinconsortium.org

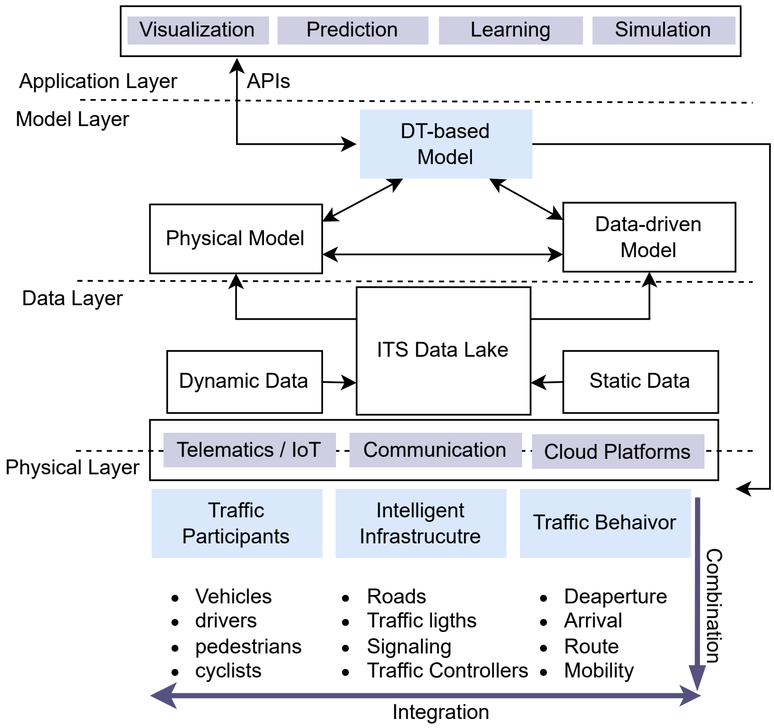

Figure 2. Digital twin framework for roads intersections.

However, there is no formal framework for developing digital twin applications in modern transport systems. Therefore, we propose a systematic framework composed of four layers shown in Figure 2 for the accurate and timely development of applications digital twins-based in intelligent intersections.

3.1. Physical Layer

The physical layer contains the elements that are part of the intersection ecosystem and the processes of their combination and integration. The layer is responsible for the main processes in any digital twin application's operation through sensing and actuation processes. Sensors distributed by the crossing scenario collect data referring to real-time processes detecting dynamic behaviors, events, and processes in general, which are transmitted to the upper layers to create models. The transmission is performed using communication interfaces and other technologies that allow close interaction between physical and virtual entities. Likewise, models based on the digital twin of the intersection generate signals or instructions to trigger the physical behavior through actuators. The physical space is defined in global coordinates, in which three functional blocks represent all the elements in the intersection:

- Intelligent infrastructure includes design tasks, physical infrastructure maintenance, and system operation management with a macro approach. Therefore, the actuation processes in this first block have a crucial human intervention component, especially in cases directly related to the design and maintenance of the infrastructure. The actions are carried out through traditional signaling elements deployed in the intersections for operational tasks.
- The traffic participants, vehicles (autonomous, assisted steering, and conventional vehicles), with vehicle monitoring through geolocation modules, perception sensors (LIDAR, Radar, Camera), and the information earned by the vehicles CAN

network. The action focuses on vehicle control variables (steering system, acceleration, brakes, among others) and drivers through driving assistance systems. Non-vehicle participants (drivers, pedestrians, cyclists, among others) are also covered. Sampling processes for these participants are carried out actively through human-machine interfaces, in-cabin sensing, ambient sensing, or passively through wearable devices. The action processes are directed to drivers through driving assistance systems and pedestrians, cyclists, or passengers through signaling systems (light, sound, among others) on the roads.

- Traffic behavior and other phenomena that act directly at the intersection, such as the mobility characteristics of pedestrians and cyclists, the driving profile of the drivers, and the acting of local regulatory agencies, among others. Sensing is closely related to the information obtained by the previous function blocks. Others depend exclusively on the relationship between traffic management companies, regulatory agencies, and authorities to keep specific policies and practices up to date at each intersection.

3.2. Data Layer

The data layer is based on the collection of real-time data from the sensing and sampling processes produced in the physical layer, which, combined with historical data from the system, provide a complete data lake for the construction of the models used by the digital twin. It is recommended to collect the most accurate data possible and the most abundant information, giving the digital twin characteristics that reflect the actual state of the intersection. Depending on the processes or physical entities being monitored, the data may have i) a dynamic perception of the intersection concerning the operations of traffic participants and their behaviors, or ii) a static nature more linked to the description of the environment and infrastructure of the intersection.

3.3. Model Layer

In the model layer, the data processed in the lower layer is used to create computational models that describe the infrastructure, the elements involved in the traffic, and the operational processes of the intersection system. Physics-based models were well-behaved for the solution of physical processes and systems, but many complex systems escape such quantitative analytical descriptions. In addition to the high computational demand to be solved, in most cases not suitable for dealing with real-time applications. With the recent development of artificial intelligence and machine learning solutions, data-driven models are presented as an excellent complement to physics-based models, fundamentally supporting optimization and simulation tasks in digital twin solutions. A balanced perspective of both approaches is required for complex road intersection scenarios.

Once the digital twin model is built, it continues to receive real-time information from the intersection to stay updated and more accurate. From this digital twin model, complex simulation and decision tasks are performed. At the same time, there is feedback to the physical layer as the digital twin is updated from the simulation and analysis, modifying the physical entities and processes of the intersection. In this way, the digital twin of the intersection acts as a simulator of reality, modifying and remotely managing the intelligent intersection.

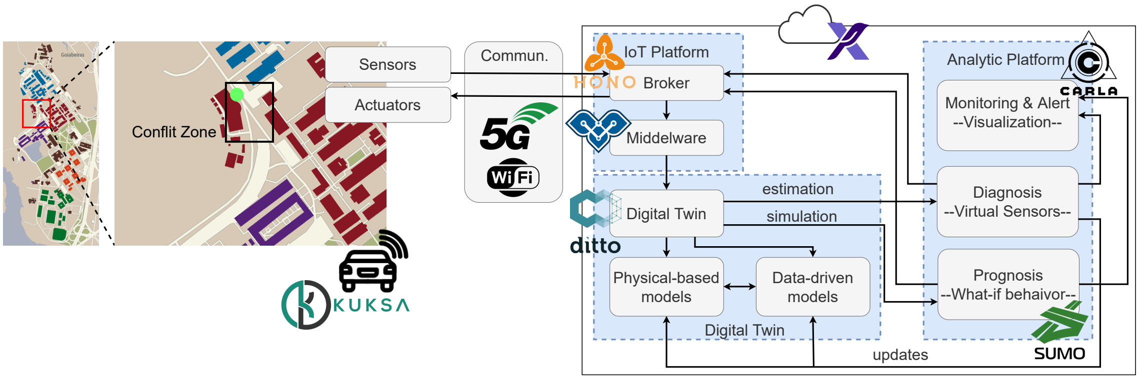

Figure 3. UFES Intersection Digital Twin.

3.4. Application Layer

The application layer is responsible for computing the different types of applications:

- Intrinsic applications of the digital twin that uses the models for simulation and analysis, learning tasks of intersection patterns, urban mobility, and visualizing current conditions of the intersection, the output of simulations and predictions. For most of these cases, the digital twin and their applications must work offline to explore different intersection scenarios without being tied to the elements of the physical world. Through the digital twin-based model, the applications help to optimize interactions to obtain unknown information and assist in decision making.
- Other applications are part of each intersection's particular solutions, consuming the model data and the results of the simulations, analyses, and predictions of the intrinsic applications for a specific purpose. The outputs of these applications are shared through visualization platforms. So the authorities responsible for the intelligent intersection can detect and isolate faults and perform specific management tasks for the assets participating in the intersection efficiently and safely.

The data lake and digital twin-based model used by upper-tier applications are always accessible due to the use of edge-cloud computing platforms on which our proposal is based.

4. Our Implementation: A Digital Twin for Road Intersection at UFES' Campus

The intersection digital twin is being implemented at the Federal University of Espírito Santo, where an intersection of interest on the university campus was selected. The intersection of type ramp merge, non-signalized, is located at the exit of a low visibility curve as shown in Figure 3. In addition, a crosswalk is located within the conflict zone.

Installed LIDAR devices and cameras carry out the sensing of the infrastructure and the elements involved in the traffic at the intersection. To obtain more detailed information on the vehicles in the crossing, the open solution Eclipse Kuksa [2] is implemented on the test vehicles. Kuksa is a platform based on micro-services for developing automotive services that use open interfaces and protocols to connect with vehicles. Through

[2] https://www.eclipse.org/kuksa/

off-the-shelf hardware, Kuksa allows access to the vehicle network for monitoring and action tasks. Both the fixed sensors at the intersection and Kuksa use 5G and WiFi wireless communication networks to access the intersection digital twin platform.

Implemented on the edge-cloud, a modular internet of things (IoT) solution is used to access and process data from the data layer. The sensing and actuation devices at the intersection connect with the Eclipse Hono broker [3] to access de platform. Hono provides remote service interfaces for physical layer devices that allow them to interact uniformly regardless of the communication protocol (Hono supports traditional IoT communication protocols such as MQTT, AMQP, and CoAP). Data and messages from the physical world are normalized into a semantic model defined by the Eclipse Vorto solution middleware [4]. For that, Vorto defines a domain-specific language that allows describing digital twin models and offering the possibility of saving them in a public repository for reuse.

For the creation of the physical models and data-driven models that describe the digital twin of the intersection, the Eclipse Ditto solution [5] is used. Ditto is an open-source solution for building domain-independent digital twins of IoT devices. Although designed specifically for devices, the domain models created from attributes and characteristics to structure the physical world allow Ditto to be used in the creation of the intersection digital twin, describing their physical elements and processes. Ditto has several well-known APIs (HTTP, WebSocket, and Kafka) for applications to interact with the digital twin. The applications reside in the analytic platform through which they are carried out:

- Diagnostic tasks to estimate parameters and create virtual sensors.
- Prognosis tasks through analysis of what-if situations and simulations (integration with the Eclipse SUMO [6] for the simulation of traffic and mobility in general of the interception).
- Visualization tasks of both the current state and possible futures in 3D scenario simulators (integration with the 3D simulator Carla [7], creating the layout of the intersections using the openDRIVE standard and representing all the elements in the traffic and even the sensing and actuation device, as well as performing co-simulation together with SUMO).
- Specific applications to address traffic efficiency, safety, and other roads intersection solutions.

The data lake and digital twin-based model used by upper-tier applications are always accessible due to the use of edge-cloud computing platforms on which our proposal is based. The StarlingX [8] cloud infrastructure is used, designed to deploy micro-services for IoT applications distributed at the edge. This cloud solution is deployed on a low latency Linux distribution with deterministic behavior, offering the possibility to explore applications with strict latency requirements.

[3] https://www.eclipse.org/hono/
[4] https://www.eclipse.org/vorto/
[5] https://www.eclipse.org/ditto/
[6] https://www.eclipse.org/sumo/
[7] https://carla.org/
[8] https://www.starlingx.io/

5. Conclusion

Aiming at better performance and the ability to monitor and control road intersections, we propose the implementation of a digital twin for intelligent roads intersections to explore all the advantages they offer. The successful consolidation of the real testbed will allow us to develop any applications for the management of road intersections. Fundamentally, our focus is on safety applications for agents acting at the intersection. In general, safety solutions at road intersections are directed towards the behavior of vehicles, closely linked to autonomous vehicle solutions. However, we are especially interested in the safety of non-vehicle agents (pedestrians, cyclists, etc.) that generally receive less attention by intelligent transport solutions. The idea is to develop models and applications that allow the construction of scenarios, so that accident situations involving the agents above in different futures can be analyzed and understood and then act on the intersection of roads in the present to avoid such situations. Moreover, our testbed solution will also allow collaboration with the scientific community and companies that address intelligent transport topics, interested in exploring solutions based on digital twins.

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References

Bao, L., Wang, Q., and Jiang, Y. (2021). Review of digital twin for intelligent transportation system. In *2021 International Conference on Information Control, Electrical Engineering and Rail Transit (ICEERT)*, pages 309–315.

Budan, G., Hayatleh, K., Morrey, D., Ball, P., and Shadbolt, P. (2018). An analysis of vehicle-to-infrastructure communications for non-signalised intersection control under mixed driving behaviour. *Analog Integrated Circuits and Signal Processing*, 95(3):415–422.

Deka, L., Khan, S., Chowdhury, M., and Ayres, N. (2018). *Transportation Cyber-Physical System and its importance for future mobility*, pages 1–20.

Grieves, M. and Vickers, J. (2017). *Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems*, pages 85–113. Springer.

Kant, V. (2016). Cyber-physical systems as sociotechnical systems: a view towards human–technology interaction. *Cyber-Physical Systems*, 2(1-4):75–109.

Okai, E., Feng, X., and Sant, P. (2018). Smart cities survey. In *2018 IEEE 20th International Conference on High Performance Computing and Communications; IEEE 16th International Conference on Smart City; IEEE 4th International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*, pages 1726–1730.

Semeraro, C., Lezoche, M., Panetto, H., and Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. *Computers in Industry*, 130.