Damage detection and drone inspection of roads with digital twin technology

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ABSTRACT: Roads play a significant role in connecting cities to transport goods and people. Heavy usage requires constant monitoring and predictive maintenance. A digital twin is a technology aimed at representing the current state of an object and performing what-if analysis based on sensor dataflow. To reduce an error probability, gathering additional data is proficient. This paper introduces a concept for damage detection including drone inspection as a digital twin of the road system reaction. The inspection task is automatically established for the suspected damaged area.

1 INTRODUCTION

Digital twins become the main trend for modeling any physical system/process. More and more domains adhere to this concept because of its advantages. Establishing real-time sensor dataflow, coupled with corresponding digital models, i.e., *physical → digital connection*, is usually referenced in the literature as *digital shadow engineering* (Kritzinger et al. 2018). Digital shadows already improve modeling performance and efficiency, especially for predictive maintenance and optimization tasks. The next stage of modeling immersion is *digital twin engineering* – designing the impact of digital counterpart's modeling results on the corresponding physical entity, i.e., *digital → physical connection*. Usually implemented in the form of decision-making, this connection is crucial for self-adaptation algorithms, allowing even better modeling quality.

This paper aims to introduce a concept of drone inspection as a decision-making response to damage detection within a digital twin of the road system. In this domain, the digital twin is a driver for predictive maintenance algorithms and improved tire-road simulations. In the presented use case, the damage detection is conducted by comparing the results of deflection measurements on the real road (physical twin), which could be conducted e.g. via the MESAS truck of BASt, to appropriate simulation results via models within the digital twin based on the current road structure. The difference between measurement and simulation results that exceeds the defined threshold indicates a potential damage and triggers additional drone inspection as a digital twin decision-making response.

2 DIGITAL TWIN USE CASE: DAMAGE DETECTION FOR PREDICTIVE MAINTENANCE

The basis for a predictive maintenance of roads is to gather its current state regularly and to observe increasing damage. For this purpose, different strategies exist. A permanent observation requires many sensors distributed over the road and is currently not available on standard roads. A frequent observation via mobile measuring devices, e.g., MESAS, is an already existing alternative. Thereby, MESAS provides among others a deflection measurement of the road surface at defined loading conditions: tire type, tire load and velocity are known, which is important to set up corresponding simulation models. The deflection measurements (sensor data) are input to the digital twin. Within the digital twin, the expected deflection can be simulated via models depending e.g. on the road construction, the current temperature state and the loading conditions. A difference between simulation and measurement that exceeds defined bounds indicates potential damage at the corresponding position and necessitates further inspection, e.g., via drones.

2.1 *Digital twin architecture*

Digital twin engineering significantly differs for various domains. The main factors that should be considered when designing a digital twin architecture are simulation performance, scale, and accuracy (Negri et al. 2017). For the use case presented, the digital twin requires multi-scale modeling for different road parts while the whole system remains vast.

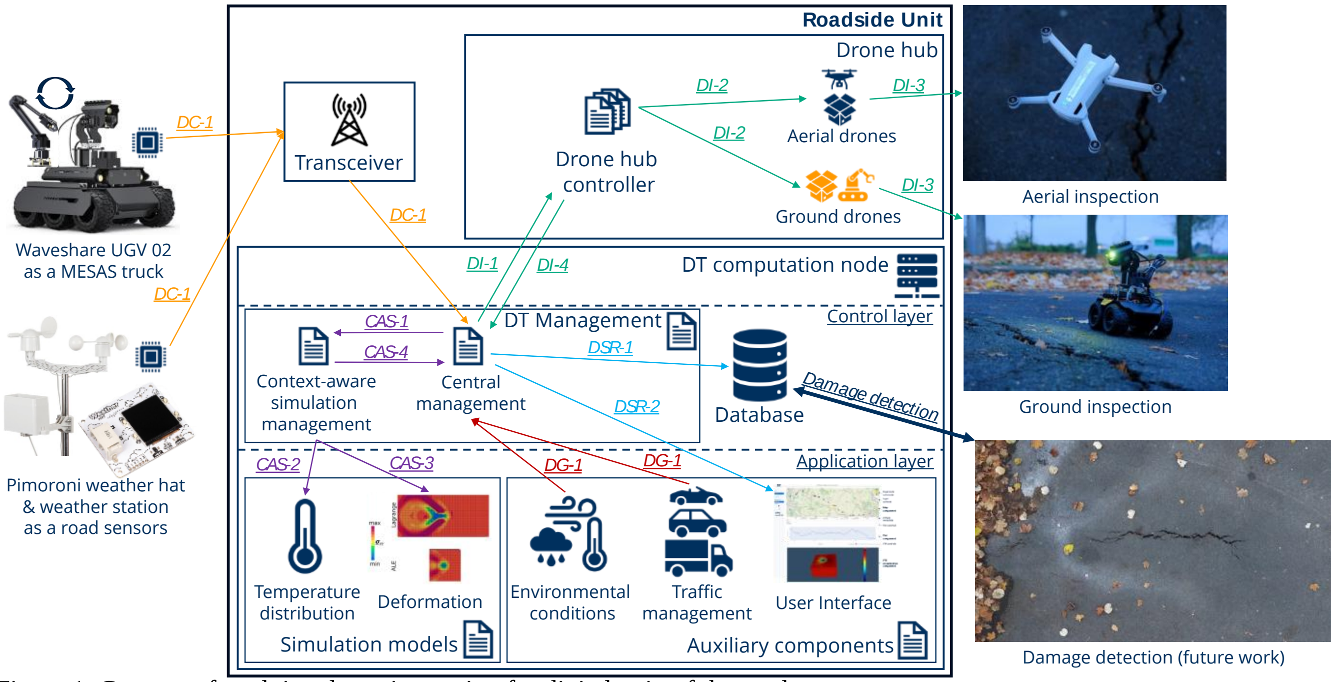

Figure 1. Concept of applying drone inspection for digital twin of the road system.

Simulation accuracy remains variable depending on demands – whether it is long-term approximate predictions or accurate road state representation. Moreover, in real-world conditions, simulations are usually not static. Taking an example of simulating vehicle-tire-pavement interaction for a moving vehicle, it is evident that, when a vehicle travels for a long distance, conditions will change many times during the trip. Weather conditions and road structures (e.g., asphalt, concrete) may change multiple times, requiring an adaptive modeling approach and appropriate digital twin architecture. Preliminary work (Prokopets et al. 2023) discussed the architecture based on a single underlying model principle. The focus of this architecture is to provide the capability to update model parameters/model itself based on specific conditions, i.e., *context-aware simulations*. This architecture is basis for the research described in this paper.

3 CONCEPT

This section provides a brief introduction to the proposed concept. Figure 1 shows hardware and software (denoted with file icon) parts and five general workflows: DC - Data Collection, DG - Data Generation, CAS - Context-aware Simulations, DSR - Data Storage and Representation, and DI - Drone Inspection. The index that follows workflow abbreviation indicates the step number in the order of execution. DC and DG workflows are commonly exclusive and dedicated to be used in different scenarios.

3.1 *Hardware part*

Drones suit inspection tasks because they can access hard-to-reach areas, reduce human risk, and improve inspection efficiency (Cabianca et al. 2022). Drones can cover most of the visual inspection tasks, including thermal inspection. Usually, a drone represents a ground/aerial platform capable of mounting additional sensors, e.g., cameras, microphones, LIDARs, RADARs, thermal cameras, radio transceivers, etc. This allows to use the drone as a universal tool for point, area, and route inspections. Copters are well suited for inspection tasks because they do not need a prepared runway and can hover over the point to make steady shots.

Drone hangars such as DJI Dock and Matternet provide a weatherproof shelter for quadcopters with wireless charging capability. Integrating these hangars allows the achievement of autonomous drone fleet management capabilities with higher efficiency in terms of lower downtime between operations and flexible scalability options. For the digital twin of the road system, utilizing drone hangars as a part of a roadside unit (RU) is considered – an intelligent transportation system component that connects vehicles and road infrastructure objects. Every RU can have various drone hangars depending on demands, forming a hub for serving assigned areas.

3.2 *Software part*

3.2.1 *General architecture*

Previously designed software architecture (Prokopets et al. 2023) is used for the current research. High-level components of this architecture form a two-layer structure with control and application layers. The control layer consists of a message broker (bus) that handles data streams between physical and digital counterparts, a twinning management component for data collection and prediction, and a context-aware simulation manager for performing variability management during simulation. The application layer is presented with various simulation models that are called depending on the respective request.

3.2.2 *Auxiliary components*

To achieve better simulation results and perform a what-if analysis, auxiliary models are required. For example, a weather forecast cannot be represented using sensor data only – an appropriate weather model is required. Moreover, usage of traffic management and geography models is crucial for the accuracy of the simulations in the digital twin of road systems. Therefore, the application layer is extended with these models.

The user interface is implemented as a dashboard for real-time state representation of the digital twin. The Dash Plotly Python library is used because of its easy integration capabilities and wide range of accompanying modules for plotting and working with map and visualization toolkit (VTK) objects. Communication with digital twin components is done via callbacks – dedicated functions triggered at specific conditions, such as user actions, inner state, or time.

Adhering to drone inspection, an appropriate drone behavior model that represents its dynamic properties (such as velocity, acceleration, and power consumption) is required. Path planning, including inspection type (point, area, route), is risky without considering this model. The model should be individually configured for every vehicle. Moreover, self-adaptability is vital to achieving better mission range and duration.

3.3 *Workflows*

3.3.1 *Physical – digital connection*

To keep the digital twin updated over the lifetime of the road, data from the real road (e.g., sensor data) are required frequently. Thereby the frequency and the kind of the required data depends strongly on the intended use case and application of the digital twin. For the damage detection proposed here, data on the thermal conditions (e.g., data from weather stations and temperature sensors) and data of the deflection measurement including the measured displacement as well as the loading conditions (tire type, load, driving velocity) is required along the inspected road section (*DC-1*). For predictive maintenance simulations, step *DC-1* will be replaced with *DG-1*. All collected/generated data can be stored (*DSR-1*) and represented via the user interface (*DSR-2*). Thereby, digital twin software and backends do not need to be built from scratch for each application. The FIWARE platform e.g., offers a curated collection of open-source software components that can be integrated with third-party tools to accelerate the development of smart solutions across domains. It enables the modeling and deployment of digital twins, such as a digital twin of a road, incorporating structural data, various sensors and computational models (Hildebrandt et al. 2024).

3.3.2 *Context-aware simulations within the digital twin of the road system*

To simulate the deflection of the road realistically, finite element simulations of the layered pavement structure can be conducted. Required inputs are geometric data of the investigated road (layers, materials) e.g., from geometric-semantic models or a database within the digital twin (*CAS-1*). To consider the temperature dependent behavior of pavements, a thermal simulation is conducted first that considers the measured weather conditions and temperatures to get the current temperature field inside the pavement structure. Thereby, due to changing conditions along the road (sunny/shaded areas, local rain, different road constructions), the temperature field changes along the road; thus, for each section, a separate thermal model is required (*CAS-2*). Then, the mechanical finite element models are called for each section that simulate the displacement field of the road subjected to the rolling tire considering the temperature dependent material properties e.g., of asphalt. Depending on the driving condition (steady state or dynamic rolling) different simulation models are available (Wollny et al. 2016, Anantheswar et al. 2024) and called (*CAS-3*). To save computational time, model order reduction (MOR) can be applied to speed up the simulations (Zhang et al. 2024). The simulated deflection is compared to the measured deflection (*CAS-4*). A significant deviation between both values indicates a potential damage (e.g., crack propagation).

3.3.3 *Digital – physical connection*

Decision-making is used as a response action to simulation results. Based on the results of *CAS-4*, drone inspection should be performed for a position if the difference is too high. Thus, an optimal path from the closest RU to the warning location should be built, followed by an inspection type definition. The result is a waypoint mission – a set of points in format *latitude*, *longitude*, and *altitude*, together with *camera gimbal angles* for inspection points. Any triggering event, like a deflection measurement warning, road user complaints, etc., triggers the creation of a warning object, displayed as an exclamation mark sign on the dashboard's map. This object contains meta information such as location and a short description. The closest RU adds this warning to its pool (*DI-1*). The drone hub management generates the inspection task in the form of a waypoint mission described above (*DI-2*). As a result, an image dataset for defined areas is collected along with drone telemetry (*DI-3*). The latter is helpful for self-adaptation to improve the mission planning in the future. The collected data is assigned to the warning objects and can be displayed in the dashboard (*DSR-2*). A damage detection algorithm is planned to be used to identify damaged parts.

4 PROOF OF CONCEPT

4.1 *Synthetic benchmark*

As a first step towards concept evaluation, a synthetic benchmark representing the highway system between Dresden and Leipzig is created. A road user may appear at an arbitrary connection point with other roads and then lead towards another connection point. A simulation of road structure temperature distribution and deformation under load is handled individually for every vehicle. Simulation results can be accessed via the dashboard. A measuring laboratory is a vehicle capable of measuring deflection. At the current state, the measuring results are artificially generated. Roadside units are placed along the highway approximately every 10th kilometer. The supplementary video describes the main components of a user interface and an exemplary use case scenario simulation (https://tud.link/eyua5p). Traffic management, roadside unit, and environmental condition modules can be configured using JSON files, making testing different simulation scenarios possible.

4.2 *Small-scale experiment setup*

In addition to the synthetic benchmark, small-scale experiments using DJI Mini 3 drone and Raspberry Pi-driven Waveshare rovers are currently being prepared. Another Raspberry Pi with connected weather sensors will play the role of the roadside sensor by gathering sensor data and sending it to the roadside unit node. The main-node PC will represent the DT computation node and execute simulation models, generate inspection tasks for assigned drones, store data, and display it using the interactive dashboard.

4.3 *Limitations*

The proposed concept of drone inspection has several limitations that need to be discussed in this paper. One limitation is operational safety. Flying routes should be planned to avoid legal regulation violations, driver distraction, and collisions with road objects. Another limitation comes from the type and size of drones used for inspection. Usually, inspection drones are small for safety reasons and because of the requirements to have the ability to fly in narrow spaces. All this leads to operating range limitations and vulnerability to bad weather conditions. Thus, inspection tasks for large areas require a risk assessment for every operation and a dense RU network or mobile drone hubs as an infrastructure.

5 CONCLUSION

The concept of autonomous drone inspection as a digital twin response to simulation results is promising. A vast network of RUs equipped with drone hubs allows for gathering road state information much faster and cheaper than traditional inspections. Existing drone image processing software, such as WebODM, enables the generation of maps, point clouds, digital elevation models, and 3D models from aerial images. Representation of this data using an interactive dashboard allows road maintainers to better visualize the current road state and plan predictive maintenance.

Future research should address the current limitations, i.e., scalability, safety, and cost-efficiency. Swarming drones increase the flexibility of their usage, which helps to reach these targets. Defining adaptive image processing for perspective (from ground drones) and orthogonal (from aerial drones) images is another topic for future work.

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