DesCartes: Hybrid Artificial Intelligence for optimal planning and decision making in urban systems

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1. Introduction

Intelligent modelling technologies such as digital twins, applied to urban infrastructures and systems, can enhance community-centric planning by simulating urban environments and developing predictive scenarios in response to critical and uncertain situations, allowing both optimal planning and aided or even automated real-time decision-making. This paper revisits the main methodologies and some proofs of concept developed within the DesCartes programme leaded by CNRS@CREATE.

2. Methods

Concerning the virtual representation, for design and operation of a given asset (component, system and/or complex system of systems), two levels of digitalization (two classes of digital twins) can be distinguished.

The first level, leading to the so-called *digital twin prototype*, concerns the virtual representation of the asset, equipped with its physics-based behaviour, enabling the emulation of the asset operation. The digital twin prototype is composed by a state-of-the-art physics-based model, that from the assumed inputs (actions) predicts the asset (component or system) responses, to evaluate if the requested performances and robustness are ensured. This digital twin, purely virtual, precedes the existence of the asset, and precisely, it is used for optimal design purposes. When possible, it can assimilate existing available data, making possible the use of generative design technologies.

The main protagonist of the second level of digitalisation is the so-called *digital twin instance*, that comes into the scene as soon as the asset exist and operates, enabling real-time diagnosis, prognosis and decision making. It includes also data, sent from the asset to the virtual computational model (to ensure monitoring) and from the virtual model to the asset for control purposes.

In both cases, an accurate and agile model is needed, providing the asset response to any input. Here, the main question concerns the nature of that model. Two main possibilities exist.

- Physics-based models use the existing knowledge expressed mathematically from a system of coupled partial differential equations, reflecting the coupled nonlinear multi-scale and multi-physics behaviours, with a series of constraints and domain knowledge. The main limitation of such an approach is the loss of accuracy in long-time predictions because of the limitations of models to exactly represent the observed reality.
- Data-driven models learn from the available data, however, in engineering, data is constrained by the cost of sensors, the difficulty of its massive deployment, the data transmission, storage and treatment, … Thus, the construction of fields from the, usually scarce, collected data, needs some approximations with their intrinsic loss of accuracy.

Increasing the amount of measurements becomes unreasonable, and sometimes impossible because of the existing regulations.

A gateway consists of combining both paradigms into an hybrid one, in which data is not used to learn the model itself, but to learn the gap between the physics-based model predictions and the measures. If the available physics-based model is accurate enough, the gap is expected being small enough to facilitate its approximation from few data points, enabling not only to explain the resulting hybrid model, at least its physics-based component, but also reducing significantly the amount of required data to reach high accuracy in the predictions, reducing the environmental imprint. Moreover, the physics knowledge enables to drive the data collection, within the so-called active learning paradigm, that is, determining the data to be collected, and the location and time at which performing the measures.

The hybrid modelling [1-3] proceeds as follows:

- Using machine learning to construct the physics-based model surrogate from high-fidelity simulations, able to proceed in real-time while ensuring high levels of accuracy.
- For the different available states of the asset, data is extracted (measurements performed at the optimal locations and times). These measures are compared with the predictions provided by the model. The difference (gap) only known at the measurement points, is extended everywhere in the physical domain (data completion). Now, a new surrogate is constructed but this time modelling the gap (gap model).
- The hybridization performs as soon as the surrogate of the physics-based model and the model of the gap are available. From both, one is tempted to improve predictions by adding to the physics-based prediction the enrichment (or correction), to obtain the so-called hybrid solution.

2.1 Towards a city hybrid twin

The DesCartes integration workflow is sketched in Fig. 1 where the fundamental research gives rise to implementable algorithms, that integrate the so-called hybrid-twin combining surrogates of physics-based model (able to operate under the stringent real-time constraints) with data-driven models of the prediction to measurement biases (the gap or physics-based model ignorance), most of time consisting of informed learning.

These hybrid twins are then applied to model the different system components, that at their turn are integrated in the so-called "control tower", the system of system hybrid twin, that could and should be advantageously employed for taking decisions, and eventually informing people, governmental services and authorities, able to proceed with optimal operation or with mitigation procedures in case of emergencies.

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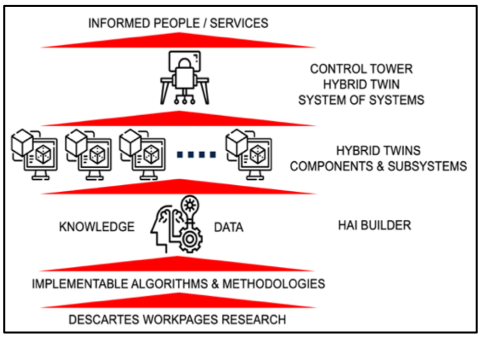

Fig. 1: DesCartes: from research to decision making

DesCartes considers different demonstrators (Fig. 2): (i) the city environment hybrid twin; (ii) the digital energy; (iii) remote sensing of large civil, urban or industrial infrastructures; (iv) drones trajectory planning, as the ones employed for monitoring, gods' delivery, or mobility; and (v) management of emergency crises.

Fig. 2: Descartes demonstrators developed in collaboration with industry and agencies

Concerning the city hybrid twin, applied to Marina Bay district (in Singapore) and La Defense district in Paris (France), the main protagonist was the wind, intimately coupled with many other physical phenomena (temperature, noise, air quality, plume dispersion, drone trajectory planning, …) as illustrated in Fig. 3.

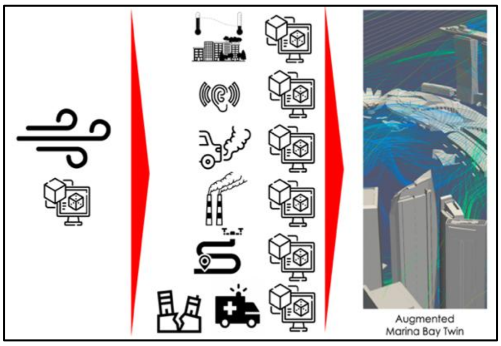

Fig. 3: Environmental digital twin

2.2 Real-time maps

Following the rationale described above, the wind at large-scale is parametrized by its intensity and direction (available in real-time from satellite data), considered as boundary conditions in the computational fluid dynamics model and its simulation.

High-fidelity simulations for different far-field wind conditions are carried by using OpenFOAM CFD opensource software, that computes the different wind fields in the considered urban area. A valuable ML-based regression connects the wind fields with the satellite data (far-field wind intensity and orientation) to define the wind surrogate (wind map). From some data, the wind map can be enriched within the hybrid modelling paradigm.

With the wind map available, different physics depending on it can be addressed. Air quality depends on the wind in each street, the density of traffic and the cars velocity distribution. By using state-of-the art models, the air quality can be estimated.

Emissions dispersion can be also easily evaluated from the wind map. A passive scalar is advected by the wind. Thus, many scenarios can be simulated in almost real-time to take certified decisions.

A temperature map can be also elaborated by using the same rationale employed for computing the wind map, to infer, depending on the solar intensity and the wind conditions, the temperature at the ground and on the building's walls, as well as the effects induced by temperature on the wind velocity field (thermo-convective flows).

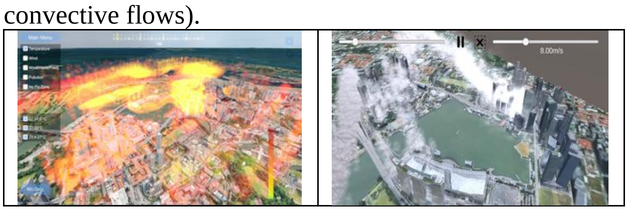
Fig. 4: Temperature map (left) and plume dispersion (right)

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