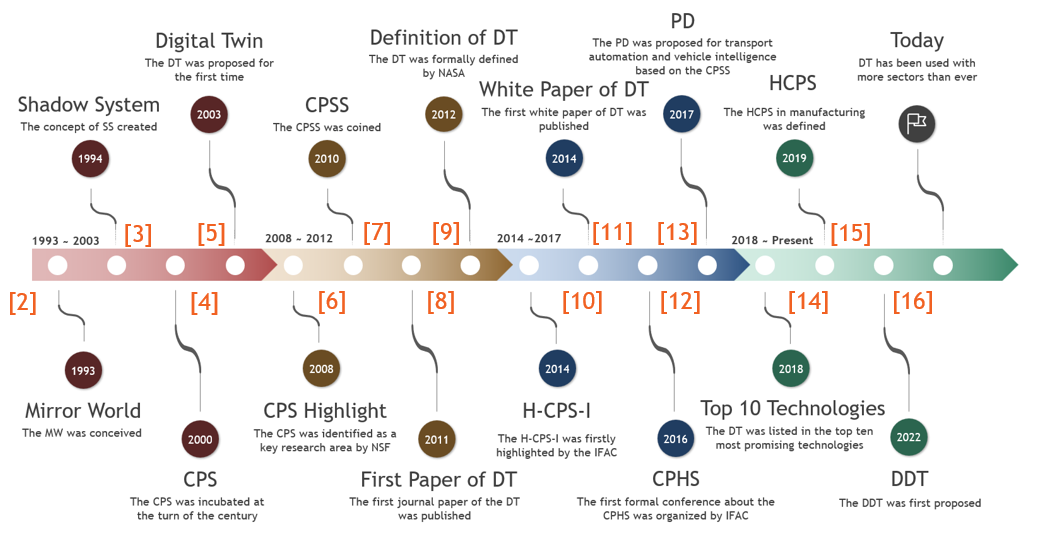
**High Performance Computing for Developing Hierarchically Consistent Digital Twins for Autonomous Vehicles using the Real2Sim Approach**

**Tanmay Samak**

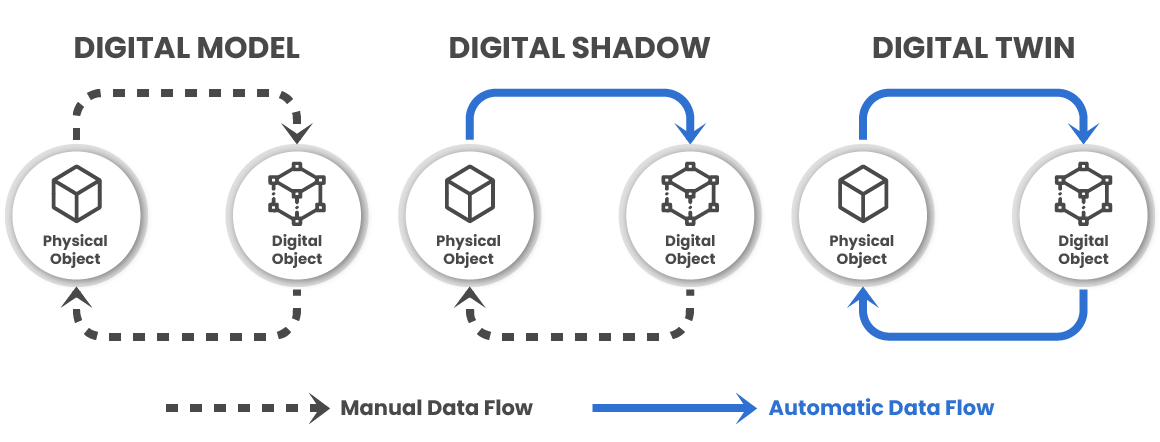
# 1. Introduction

Modeling and simulation form an integral part of moving from reality to simulation (real2sim). These models could be first principles models (white-box) including rigid-body – kinematics, dynamics and contact models; soft-body – continuum, truss and finite-element models, multi-physics – bond-graph and object-oriented models; small-scale statistical models (grey-box) including system identification – parameter estimation; curve fitting – polynomials, splines, Gaussian process based models; large-scale neural models (black-box) using machine learning techniques (supervised/un-supervised/reinforcement learning).



**Figure 1.** Origins of digital twin technology [1]

Although modeling was practiced since a long time, it was John von Neumann and Stanislaw Ulam who first used these “models” and computationally simulated the behavior of neutrons in a nuclear shielding problem for the first time. This way, in addition to just having models, solvers that performed numerical time-stepping and integrating the evolution of their states over time became common. Later, kinematic and dynamic simulations for mechanism design and analysis started becoming common wherein the results were often mere numbers or time/frequency domain plots describing the system behavior. Going further, as the complexities of these models grew and the number of states exploded exponentially, it became highly intractable to analyze their behavior and benchmark their performance using just numbers or plots. This is when advanced visualization features such as motion analysis, animation and photorealistic rendering started becoming very popular and demanding. Finally, especially in the context of autonomous mobile robots and vehicles, features such as extended application programming interfaces (APIs) to multiple software frameworks and programming languages as well as user-friendly graphical user interfaces (GUIs) have started to become a recent popular demand.



**Figure 1.** Distinction between different stages of the digital thread [17-19].

Moreover, recent technological developments have given birth to and popularized the notion of digital twins. Origins of digital twins can be traced back to the concept of mirror world [2] for real-time geographically accurate representations with data-driven updates, which was followed by shadow systems [3] for engineering applications with one-way data flow & updates, succeeded by cyber-physical systems (CPS) [4] and cyber-physical social systems CPSS [7] involving social interactions, feedback and cooperation, finally leading to the modern-day digital twins [5], [9], [11] encompassing two-way data flow and updates in real-time.

# 2. Motivation

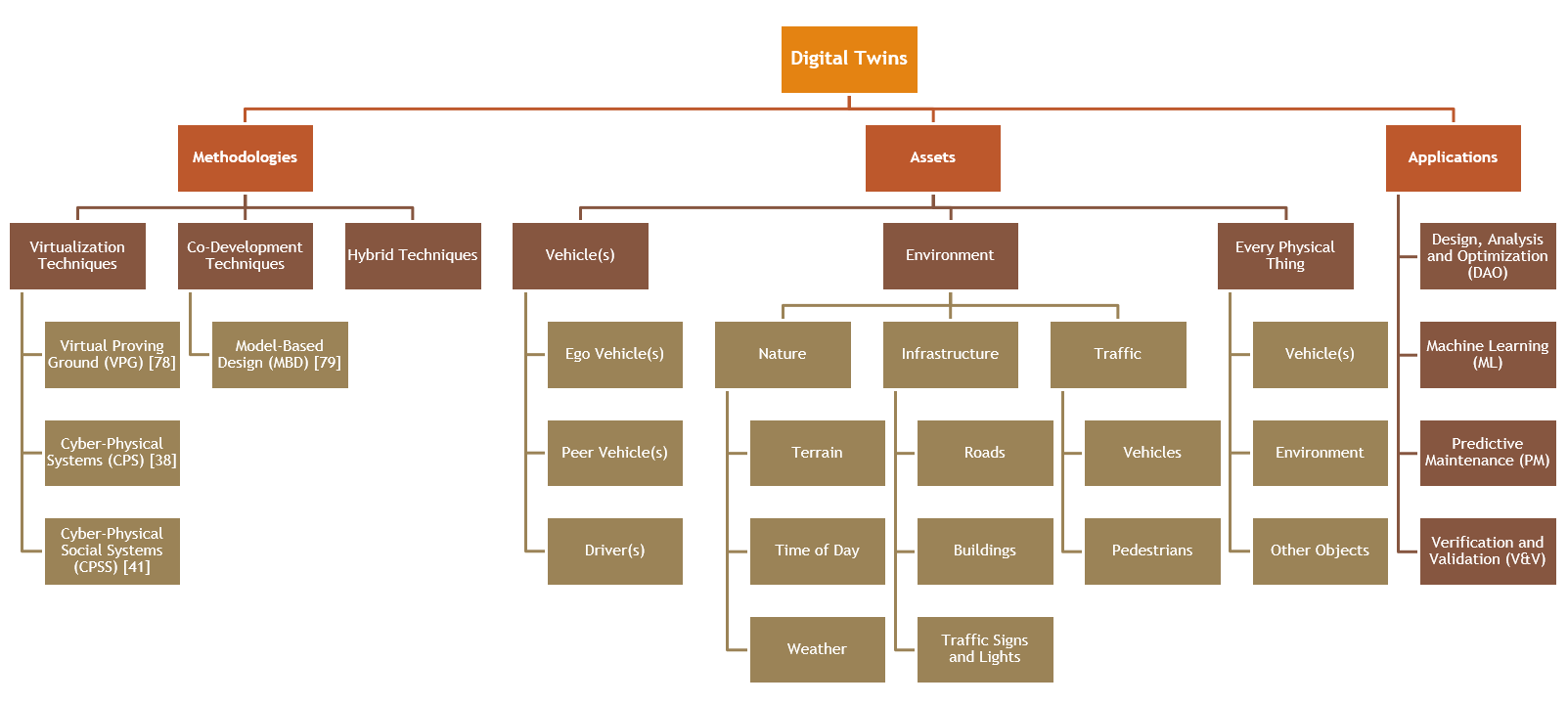
Specifically, in the context of autonomous vehicles, high performance computing (HPC) plays a crucial role in developing hierarchically consistent digital twins using the real2sim approach. To reiterate, digital twins are virtual models that replicate the behavior and performance of physical entities in real-time [20]. They have been successfully applied in various industries, including medicine, manufacturing, and now in the autonomous vehicle industry [21]. The real2sim approach involves creating a digital twin that closely resembles the real-world vehicle and the environment its operating in and using it to simulate and test different scenarios and conditions [22].

One of the key challenges in developing digital twins for autonomous vehicles is ensuring the consistency between the digital twin and the real vehicle. This consistency is crucial for accurate simulation and testing. [23] discuss the importance of consistency in digital twin test methods and real vehicle site validation for intelligent vehicles. They propose a digital twin parallel test system that combines real-time parallel simulation and 5G cellular mobile technology to achieve more challenging tests. This approach accelerates the research, development, and evaluation of autonomous vehicles and reduces the possibility of human error.

To enable efficient task offloading in autonomous vehicles, [24] propose a Digital Twin (DT) empowered task offloading framework for the Internet of Vehicles. This framework leverages the high mobility of vehicles, the dynamics of wireless conditions, and the uncertainty of computing tasks to determine the optimal offloading strategy. By using digital twins, vehicles can offload computing tasks to mobile edge computing infrastructure, improving performance and reducing latency.

High-performance computing is essential for developing hierarchically consistent digital twins for autonomous vehicles. As described in [25], the development of an automatic driving simulation test system based on digital twin technology. This system utilizes the rapid development of 5G infrastructure and cloud computing to test and evaluate autonomous vehicles safely and efficiently. The digital twin-based simulation allows for extensive testing and evaluation before deploying vehicles on real public roads.

# 3. Literature Survey



**Figure 2.** Breakdown of current state-of-the-art literature

The rich state-of-the-art literature in this domain can be broken down based on the methodology adopted for creating the digital twins, the assets (vehicle, environment, etc.) that are under consideration for developing digital twins, and the application space of these digital twin models. Here, I have presented a literature survey primarily considering the method of conceiving digital twin models with a secondary focus on the assets under consideration and their applications in autonomous vehicle domain.

* **Virtual Proving Ground (VPG):** This technique involves accurately modeling, estimating and simulating an existing real-world scenario, with a prominent focus on variability testing, corner-case analysis, and design optimization.
* **Cyber-Physical Systems (CPS):** This method involves instrumenting a physical asset with sensors and communication equipment to measure and transmit real-world data through the digital thread to update the digital twin, and vice-versa.
* **Cyber-Physical Social Systems (CPSS):** This method uses CPS as a substrate and focuses on modeling, estimating and simulating social interactions, feedbacks and coordination amongst multiple agents.
* **Model Based Design (MBD):** This technique proposes simultaneous development of the physical and digital twins withing a concurrent engineering framework, wherein the virtual prototype developed in the first half of its lifecycle is converted and employed as a digital twin in the other half of its lifecycle.

**Table 1.** State-of-the-art literature for virtual proving ground (VPG) methodology

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Article/Author** | **Methodology** | **Tools/Frameworks** | **Twin objects** | **Application** | **Summary** | **Year** |
| **Atorf et al. [26]** | VPG | Experimentable Digital Twin (EDT) | Vehicles, environment, traffic | PM | Interactive analysis and visualization for vehicles and robots | 2018 |
| **Chen et al. [27]** | VPG | Generative Adversarial Network (GAN) | Environment, traffic | V&V | Safety-critical scenario generation for motion planning | 2019 |
| **Culley et al. [28]** | VPG | Gazebo, Robot Operating System (ROS) | Vehicle, environment | DAO | System design for autonomous racing vehicle | 2020 |
| **Fremont et al. [29]** | VPG | LGSVL Simulator | Environment | V&V | Scenario-based testing of autonomous vehicles | 2020 |
| **Wu et al. [30]** | VPG | CARLA Simulator | Environment, traffic | ML | Model-based RL in autonomous driving | 2021 |
| **Wang et al. [31]** | VPG | Unity, SUMO, MATLAB, Python, AWS | Vehicles, environment | DAO | Personalized adaptive cruise control (P-ACC) | 2021 |
| **Malayjerdi et al. [32]** | VPG | Unity, Metashape, Autoware | Environment | V&V | VIrtual testing of autonomous vehicles | 2021 |

**Table 2.** State-of-the-art literature for cyber physical systems (CPS) methodology

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Article/Author** | **Methodology** | **Tools/Frameworks** | **Twin objects** | **Application** | **Summary** | **Year** |
| **Schwarz et al. [33]** | CPS | National Advanced Driving Simulator (NADS) | Environment | DAO | Digital map aware enhancement of electronic stability control (ESC) | 2010 |
| **Eleonora et al. [34]** | CPS | Gazebo, ROS | Vehicles, environment | DAO | AGV logistics action optimization | 2017 |
| **Chen et al. [35]** | CPS | Unity Engine | Drivers | V&V | Predict future actions of neighboring vehicles | 2018 |
| **Veledar et al. [36]** | CPS | IoT4CPS Framework | Vehicles | V&V | Safe and secure integration of IoT into AD | 2019 |
| **Liu et al. [37]** | CPS | Unity Engine | Vehicles, drivers | V&V | Multi-sensor fusion for vehicle recognition | 2020 |
| **Liu et al. [38]** | CPS | Unreal Engine | Environment | V&V | Infrastructure-vehicle cooperative driving | 2021 |
| **Wang et al. [39]** | CPS | Unity Engine | Vehicles, drivers, environment, traffic | V&V | Cooperation at non-signalized intersections | 2021 |
| **Staczek et al. [40]** | CPS | Gazebo, ROS | Vehicle, environment | V&V | AGV logistics action testing | 2021 |

**Table 3.** State-of-the-art literature for cyber physical social systems (CPSS) methodology

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Article/Author** | **Methodology** | **Tools/Frameworks** | **Twin objects** | **Application** | **Summary** | **Year** |
| **Wang et al. [41]** | CPSS | Artificial societies, Computational experiments and Parallel execution (ACP) | Vehicles, environment | DAO | Parallel transportation management systems | 2010 |
| **Wang et al. [42]** | CPSS | ACP | Every physical thing | DAO | Smart society | 2016 |
| **Liu et al. [43]** | CPSS | Panosim, ACP | Vehicles | DAO | Parallel driving using descriptive, predictive, prescriptive and real vehicles | 2019 |
| **Lu et al. [44]** | CPSS | EuArtisan framework | Every physical thing | DAO | Parallel factories | 2022 |
| **Wang et al. [45]** | CPSS | CARLA, SUMO, Unity, Redis | Vehicles, traffic environment, pedestrians | V&V | Vehicle-to-Pedestrian (V2P) warning system | 2023 |

**Table 4.** State-of-the-art literature for model-based design (MBD) methodology

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Article/Author** | **Methodology** | **Tools/Frameworks** | **Twin objects** | **Application** | **Summary** | **Year** |
| **Laschinsky et al. [46]** | MBD | Virtual Test Drive (VTD) | Vehicles | V&V | Vehicle-in-the-Loop (VIL) validation of active safety lights | 2010 |
| **Shikata et al. [47]** | MBD | Unity Engine | Vehicles | V&V | Electric Vehicle (EV) automatic parking and charging design and test | 2019 |
| **Dygalo et al. [48]** | MBD | Custom Testbenches | Vehicle sub-system, system and system-of-systems | V&V | Vehicle active safety technology system | 2020 |
| **Wagg et al. [49]** | MBD | MATLAB | Infrastructure | DAO | Shaking three-store building | 2020 |

**Table 5.** State-of-the-art literature for hybrid methodologies

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Article/Author** | **Methodology** | **Tools/Frameworks** | **Twin objects** | **Application** | **Summary** | **Year** |
| **Wang et al. [13]** | CPSS, MBD | ACP, iHorizon | Vehicle, driver, environment, traffic | DAO | Intelligent energy management for autonomous EVs | 2017 |
| **Rassolkin et al. [50]** | CPS, MBD | ISEAUTO autonomous shuttle bus | Vehicle sub-systems | V&V | Test stand for electric propulsion drive systems (EPDS) of self-driving EVs | 2019 |
| **Ge et al. [51]** | VPG, CPS, MBD | LTE-V2X framework | Vehicles, environment | V&V | Virtual, hybrid and physical testing of autonomous vehicles | 2019 |
| **Szalai et al. [52]** | CPSS, VPG | Unity, SUMO | Vehicles, traffic, pedestrians | V&V | Mixed-reality ADAS/AD validation | 2020 |
| **Yu et al. [53]** | MBD, CPS, CPSS | Structural, physical and logical twin framework | Environment, sensors, traffic | V&V | ADAS/AD software design and test | 2022 |

# 4. Conclusion

In conclusion, high-performance computing is crucial for developing hierarchically consistent digital twins for autonomous vehicles using the Real2Sim approach. Digital twins enable accurate simulation and testing of autonomous vehicles, reducing the possibility of human error and improving safety. The Real2Sim approach, combined with parallel testing systems and task offloading frameworks, accelerates the research and development of autonomous vehicles. With the rapid development of technologies such as 5G and cloud computing, digital twin-based simulation and testing systems are becoming more efficient and effective in ensuring the safety and performance of autonomous vehicles.

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