# Towards the Virtual Human Simulator

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Abstract: Up-to-date technologies make it possible to acquire a considerable amount of data, for a considerable period of time. It follows the possibility to strategically count on the necessary and useful elements to characterize from simple to very complex systems. Acquisition, even prolonged, and characterization of data from a certain source (object, component, system, etc.) make it possible to create a virtual copy of this source, namely Digital Twin (DT). When technology of DT meets smart algorithms of machine learning and artificial intelligence, the Intelligent DT (IDT) arises. DTs and IDTs are successfully adopted in electronics, mechanics, chemistry, but can they be applied for the entire human body so to realize a virtual human simulator (VHS)?.

## 1 INTRODUCTION

Sensors, transducers and related electronics allow gathering huge amounts of different types of data from any particular system during long time periods. In principle, this means to count on all the necessary elements to fully describe any physical system, such as an object, a component, a mechanism, a network, an implant, a machinery, a structure, potentially of any level of complexity, whether inanimate, vegetative, and animate too.

A complete description gathered from data potentially allows making a full virtual copy of any system in a digital format, namely a Digital Twin (DT). An uncomplete description allows making a partial virtual copy, namely a Model, which corresponds to a sort of limited version of the DT.

Electronic technicians virtually assemble models or DTs of electronic components to simulate their interactions in a network before making its real counterpart, since the very early 1950's when an electromechanical-relays based computer was successfully adopted for simulating the sinusoidal steady state of a linear network (Graham, 1953). Starting from that first experience, new fields of computer-aided circuit analysis and computer-aided design science were born.

Apart specific cases, an evolution occurred to land nowadays from limited concept of Model to the broader concept of DT.

A key step was the introduction of the conceptual idea of Product Lifecycle Management (PLM), by M. Grieves (Florida Institute of Technology) on 2002 (Grieves, 2005), as an efficiency-promoting paradigm for complex, manufactured products. In particular, within the concept of PLM is a real space that furnish information to a virtual space where data are elaborated to give useful knowledge to run processes in the real world. The virtual space is also made of subspaces to partialize possible simulations, such as modelling, testing, optimization, etc. (Figure 1). Within this frame, "lifecycle" emphasizes the dynamicity of the process through the phases of creation, production, operation, and disposal.

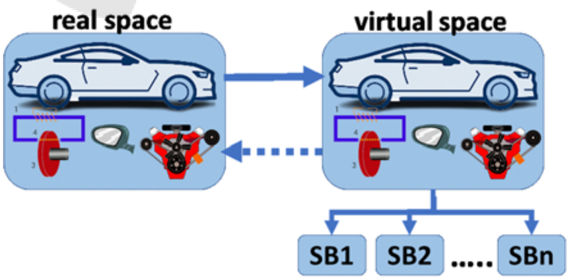


Figure 1: Conceptualization of PLM as a mirroring or twinning between a real physical system and its virtual counterpart. Data flows are from the real to the virtual space, information process flows are, vice-versa, from the virtual to the real space, the virtual space is arranged in virtual subspaces 1, 2, .. n.



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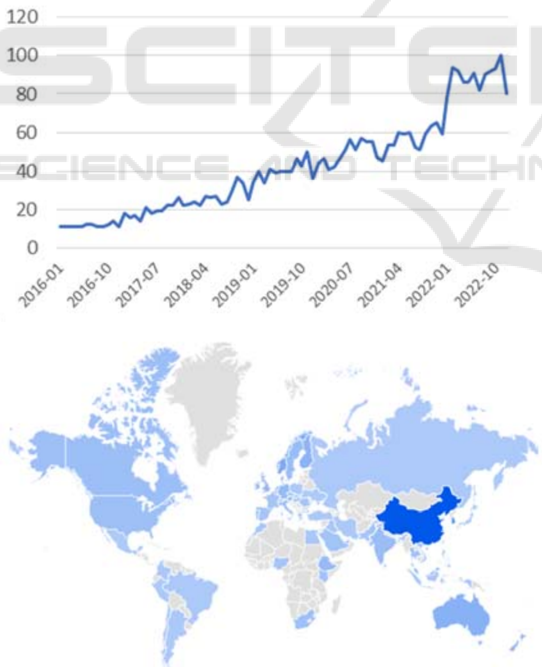
## 2 DIGITAL TWIN

The concept of PLM for industry was referred as Mirrored Spaces Model (MSM) for a university course, and as Information Mirroring Model (IMM) for a seminal book (Grieves, 2006), and later in a more descriptive way as Digital Twin (DT) as "*a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level*" in a paper dated 2011 (Grieves, 2011).

To further complicate matters, the terms Digital Angel (DA), and Virtual Entity (VE) were introduced too.

DT has becoming more and more crucial for realizing the "Industry 4.0" paradigms, as already implemented by several companies, such as Siemens, Toyota, DHL (Dohrmann et al., 2022), Philips (van Houten, 2018), IBM (IBM website, 2022), General Electric (GE website, 2022), Oracle Corporation (Puri, 2017), Microsoft, to cite a few. The interest on DT is witnessed by the increasing google search (Figure 2a,b), and the number of published papers (Figure 3) during the latest years.




a)

b)

Figure 2: a) Growing interest in google search od "Digital Twin" since 2016, b) as differenced in Countries, the China being the most active (grey colour is related to few searches, light blue and blue the Countries with major numbers of searches).

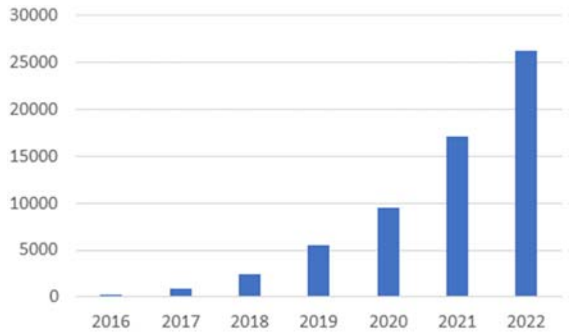



Figure 3: Number of papers including the words "Digital Twin" from 2016 (263) to 2022 (26,200).

The effectiveness of the DT strictly depends on how faithful is the virtual entity with its real counterpart. Virtual vs. real correspondence depends on data gathered from the real world (Figure 1), in particular their number, accuracies, levels of significance and abstraction (Jones et al., 2020). Moreover, the correspondence is based on the algorithms that, depending on data, describe the physical system, and on processes that foreseen actions to be done to the real part (Kuhn, 2017; Rosen et al., 2015; Boschert et Rosen, 2016).

DT, as a complete virtual description of a physical product that is accurate to both micro and macro level, splits into:

- Digital Twin Prototype (DTP): the virtual description of a prototype product, containing all the information required to create the physical twin
- Digital Twin Instance (DTI): specific instance of a physical product that remains linked to an individual product throughout that products life
- Digital Twin Aggregate (DTA): the combination of all the DTI
- Digital Twin Environment (DTE): a multiple domain physics application space for operating on DTs, including performance prediction, and information interrogation

When the DT meets artificial intelligence, machine learning and deep learning algorithms (Costantini et al., 2022), the paradigm of Intelligent Digital Twins (IDTs) arises (Grieves, 2022; Sahlab et al., 2021). The way is from simulation (as counterfeiting) of reality (a simplest copy of the real) to replication of reality.

The introduction of the DT and the increased time devoted to it with respect to its real counterpart has been leading to a number of advantages:

- The reduction of tests and checks (and, consequently, time and cost savings)
- Time-to-market reduction

- Lower any product defect
- Intercept potential problems before happen
- Simulating events without causing them in the real system
- Evaluate aging effects
- Evaluate all parameters at once avoiding considering them one-by-one
- Limit the production as a final step only

To evidence those advantages, we can consider the potential stream of a generic physical system, which can evolve into predicted or unpredicted behaviours, which can in turn evolve into desirable or undesirable (Figure 4).

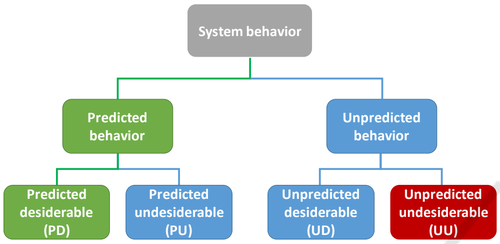



Figure 4: Classifications of all possible evolutions of a physical system (Grieves & Vickers, 2017).

Predicted Desirable (PD) is the designed class; Predicted Undesirable (PU) is related to unsolved problems (to be taken into account to avoid lawsuits); Unpredicted Desirable (UD) does not result in problems but is an index of incompleteness or the adopted model; Unpredicted Undesirable (UU) holds potential serious and dangerous problems that must be mitigated or solved. The latter is the class for which DT can be strategical advantageous.

According to the aforementioned advantages, the concept of DT has been successfully adopted in many different areas, such as aerospace (Caruso et al., 2020; Piascik et al., 2020), automotive, manufacturing (Lu et al., 2020), production (Wagner et al., 2019), industrial and consumer packaged goods, food process (Verboven, 2020), pharmaceuticals industries, energy management (Agouzoul et al., 2021), maintenance optimization (Xia & Zou, 2023), distribution grid (Jiang et al., 2022), and more.

# 3 VIRTUAL HUMAN SIMULATOR

Among all, the most disruptive area of application of the concept, of whatever DT or IDT, is in the medical one, for which an evolution is towards the Human Digital Twin (HDT), also named as Virtual Human Simulator (VHS).

VHS is not just a simple evolution of DT. The latter refers to a physical system, VHS refers to a behaviour, biological and physical system in an ensemble.

## 3.1 Steps

The higher the correspondence between the real and the virtual, the higher the number of possibilities the VHS allows, as described in the following points mentioned with increased complexity level:

1. Digitize: analogue to digital data conversion
2. Visualize: digital representation of a physical system
3. Simulate: determine one or more behaviours of the physical system in its environment
4. Emulate: mirror a system by imitation
5. Extract: gather information from real data streaming
6. Orchestrate: virtual control or update of physical system
7. Predict: future behaviour of the physical system

The digitizing step can be considered as the results of measurements made based on a four type schematization, according to the positions of electronic sources and sensors with respect to the human body under measure (Saggio & Sbernini, 2011):

- Outside-In (sources on the body and sensors elsewhere, e.g. optical systems (Saggio et al., 2020));
- Inside-Out (sensors on the body and sources elsewhere, e.g. accelerometers (Ricci et al., 2019; Saggio et al., 2021))
- Inside-In (sources and sensors on the body, e.g. sensory gloves (Saggio et al., 2011) or electro-goniometers (Saggio et al., 2014))
- Outside-Out (sources and sensors not directly on the body, e.g. force plates (Costantini et al., 2018)).

Data gathering have been evolving from fixed sensors (Inside-In), to mobile sensors (Outside-In, Inside-Out) to immersive sensors (Outside-Out, immersive persistent ambient, ubiquitous data).

The visualizing step can be realized by means of a monitor or an hologram (Ferrari et al., 2012; Saggio & Ferrari, 2012), showing virtual (Saggio et al., 2009b) or augmented reality, going from pixels (2D on screen) to voxels (3D on metaverso), or by 3D printed structures such as human organoids (Steimberg et al., 2020; López-Tobón et al., 2019).

The simulation step can be realized by means of multi-physics software modelling mechanical, electrical, biochemical cues useful for designing proof-of-concept models of human systems and subsystems (Zheng et al., 2021).

The emulation step can provide test beds for a broad range of human behaviours experimentally (e.g. the neon project by Samsung; Caliani, 2020), useful for better understanding the human biomechanics, biophysics, biochemistry and energetics (e.g. of the ankle-foot mechanism (Au et al., 2006) or sign language implementation (Calado et al., 2021)).

The extraction step can allow determining differences between ideal vs. non-ideal behaviours (e.g. healthy vs. pathological human walking assessments (Verrelli et al., 2021)).

The orchestrating step can take advantages from the extraction step to modify the incorrect behaviour of the physical system toward the desired one (e.g. specific vitamins requirements across the human life cycle (Youness et al., 2022)).

The prediction step can provide future effects of current behaviours (e.g. dietary habits; Lentz, (2008)).

### 3.2 Behavioural Model

The behavioural pattern of an individual depends on a complex mechanism due to the contribution of environmental characteristics (climate, pollution, etc.), his/her physical conditions and evolutions (sex, age, deficiencies, impairments, etc.), psychological status and developments (family situations, working conditions, friendships, etc.), boundary conditions (holidays/weekdays, day/night, sounds/noises, etc.), and more.

Therefore, as a matter of principle, if related data are fully available a complex VHS can be potentially realized, for which every environmental characteristic, every physical development, every psychological development, and every boundary condition can be simulated, each as one of the $n$ interacting subspaces (Figure 1). As an example, we can think to a VHS identity to determine, describe and predict a child's character (Mohammadi et al., 2018).

### 3.3 Physical Model

The physical model of an individual depends on a complex mechanism due to the contribution of historical data (past muscular activities, lifestyle, type of work, etc.), metabolism, physical characteristics (Saggio & Costantini, 2020) (individual muscular forces, contact forces and joints, elastic energy in tendons, antagonistic muscle action, etc.).

Therefore, as a matter of principle, being able to count on related physical data, it is possible to create a complex VHS so to be able predicting the future muscular behaviour of an individual, as already introduced for athletes' activity (Barricelli et al., 2020).

### 3.4 Biological Model

The functioning of an individual's body depends on a complex mechanism due to the contribution of systems (circulatory, muscular, endocrine, nervous, immune, etc.), subsystems (respiratory, vestibular, endocrine, locomotor, digestive, etc.), organs (heart, liver, spleen, lungs, etc.), influenced by surrounding conditions (temperature, vasodilatation, hydration, etc.) and regulated by brain activity.

Therefore, as a matter of principle, counting on complex related data, a complex VHS can be realized. Each system, apparatus or organ can be seen as subspaces in the partialization of the possible simulations (Figure 1), all interacting in a single (on cloud) platform, as already introduced for cancer evolution issues (Greaves & Maley, 2012).

### 3.5 Data

Data for VHS can be categorized into:

- Physical, chemical, electrical
- Current (in real-time, on-line), historical (deferred time, off-line)
- Transient, permanent
- Primary (necessary, determining the accuracy degree), secondary (optional, improving accuracy)

According to previous sections, data for VHS are not "simply" limited gathered from the humans, they have to be collected from his/her surroundings too.

Collected data can be advantageously wireless sent to cloud systems to be stored and processed.

### 3.6 Development

For the VHS development, a partnership between Medicine, Biology, Engineering and Computer Science is fundamental and strategic, so to be able to monitor, Analyse, Simulate, Visualize, Manage the VHS, to make it Descriptive, Integrative and Predictive.

The creation of behavioural and biological models is made possible by data classification through Artificial Intelligence and Adaptive Networks, via machine learning algorithms. For VHS, the most appropriate models to start from are given by kernel neural network (kNN) and support vector machine (SVM).

A descriptive language for the VHS could be given by the Unified Modelling Language (UML) (Saggio et al., 2009a), by a development platform such as the XMPro (Xmpro.com, 2022), and a specific software such as the ScaleOut (Scaleoutsoftware, 2022).

### 3.7 Advantages

As an example, let's observe how VHS can be useful in a crucial sector such as that of the appropriate and safe use of medicines. It is estimated that around 200,000 people die every year in Europe from the negative consequences of drug reactions (Aynaci, 2020). This high number of deaths can be drastically reduced by implementing the VHS, simulating, as mentioned, the evolution of the parameters of the specific patient linked to the assumption of the specific drug.

Obviously, this is only one aspect (not at all negligible) of using a VHS and its possible advantages. The VHS, in fact, on the basis of the interaction of the aforementioned *n* subspaces, allows evaluating the possible side effects of a drug before it is actually administered to the particular patient or average of patients.

For example, of a drug used in subspace 1 "heart", its undesirable effects can be simulated on subspace 2 "liver", thanks to the analysis of the combined/separate effect between the two spaces.

Furthermore, the VHS allows switching from the culture of the administration of drugs/therapies based mainly on the specific pathology (*one-size-fits-all*) to one based on the specificities of the patient (*tailor-made-* o *personalized- medicine*). Moreover, the VHS allows evaluating drugs and therapies effectiveness and, consequently, producing lower costs for health assistance (Scharff, 2010). Finally, thanks to the possibility of creating scenarios and carrying out simulated tests in unlimited numbers, the VHS leads to the reduction (up to zero) of the use of laboratory animals, while predicting and developing life-saving events.

### 3.8 Key Points

Key points to effectively realize the VHS can be listed taking a cue from the four of the six "M" of K. Ishikawa, i.e. Machine, Method, Material, and Management, leading to:

- Design cooperating human body simulation algorithms (anybody modelling system), with the possibility of integrating already known models (of organs or systems)
- Determine the most suitable data collection network (e.g. wireless body area network)
- Collect the subject's history data (historical characteristics), but with an incremental system (incremental learning data) to avoid a collapse or excessive response time of the system
- Create a cloud system for data collection, storage and processing (cloud computing)
- Determine the missing necessary data (Batista & Monard, 2002)
- Select data with high information content (feature selection) eliminating those with little (noisy data) or no information content (feature extraction)
- Determine the appropriate machine-learning approach and algorithm(s)
- Design a graphical user interface (GUI) easy to consult even for non-technicians
- Create the role of supervisor(s) who highlights critical points of the approach based on the results obtained
- Test the simulation algorithms by entering known data and detecting the output data (a-priori known) verifying their correspondence to the real ones
- Evaluate the correspondences of VHS results with the real ones, to remodulate the previous points (Zhang et al., 2022).

## 4 CONCLUSIONS AND OUTLOOKS

Full information can be gathered from any real physical systems to create their virtual counterparts known as Digital Twins (DTs) (partial information leads to a Model).

Sensors, transducers and related electronics are the medium to gather information and to make real and virtual interacting.

DT has been successfully applied in a variety of different areas, in some of which it's importance become mandatory.

In particular, in the medical field a number of different virtual human organs have been realized, such as the complex heart (Levy et al., 2019).

Not limiting to one virtual organ, the DT concept can be, in principle, expanded toward the entire human being, so to land to the concept of Virtual Human Simulator (VHS).

By developing the VHS, outlooks can be:

- create connections between two different VHSs to highlight differences and critical issues
- remotely monitor the subject (progress/ regression evaluation)
- supply the drug routines for the single subject's VHS
- facilitate the possibility of moving towards non-invasive and painless medical tests.

In futuristic perspectives, the VHS technology will be able to simulate brain waves in response to generic or specific stimuli, allowing investigations about the functioning of the human brain aimed at improving neuro-technologies.

Furthermore, VHS will be able to give rise to virtual models of bacteria and viruses, allowing to study the mechanisms of interaction with the various organs of the human body up to the possible onset of pathologies, and consequently to evaluate a-priori the effectiveness of possible pharmacological remedies.

Theoretically, VHS will be possible, let’s see in practice.

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