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# Holistic Digital Twin Framework: Designing Human-Machine Systems with an Overall Situation Awareness

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**Abstract:** Context Awareness refers to the use of context to provide task-relevant information and/or services to a user. The Holistic Framework for Human-Machine System (HMS) is an architecture based on multiple factors, including a surroundings consideration, to design Digital Twins (DTs). This paper discusses some of the research challenges in understanding the context and developing context-aware DT systems. In particular, the authors gave some solutions that can improve Human-Machines Systems (HMS), such as the use of human data, meta-data and peri-data or the definition of Capacity, Availability, Possibility levels. Finally, a critical discussion is brought to caution future designs of systems such as HMS in a high risk context.

*Keywords:* Human-Machine System, Context Awareness, Holistic Framework, Digital Twin, High Risk Context, Overall Situation Awareness.

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## 1. INTRODUCTION

A Digital Twin (DT) needs a physical asset to operate, for instance, a machine, a human, or both in the case of a Human-Machine system twin. Data flows between the asset, its digital space and every structure that needs access to the twin. A study conducted in Ascone and Vanderhaegen (2022) highlighted that few people in the scientific community approach a holistic view of DTs. The defined Holistic Framework in Ascone and Vanderhaegen (2022) takes into account the service to the user, the management of data, a human model, and the consideration of the surrounding around the asset(s) in the modeling and decision processes. When humans talk to humans, they can use implicit situational information, context, to increase conversational bandwidth. Unfortunately, this ability to communicate ideas does not transfer well to humans interacting with machines (Abowd and Dey, 1999). Today, new IoT devices make it possible to achieve this by recording contextual and surrounding data. By improving the machine's access to contextual information, it produces more useful services and increase the richness of communication in the human-machine interaction. The principle of Context Awareness is the use of context to provide task-relevant information and/or services to a user. Designing efficient models with a Context Awareness depends a lot on the application domain and use case. Taking into account the context of high-risk systems, where situations are often unpredictable, presents real challenges. Abowd and Dey (1999) highlighted 3 challenges around context-aware systems that the authors have tried to address. First, one of the main challenges in the area of context-aware systems is the development of a taxonomy and a uniform representation of context types. The notion of

context is defined in section 2 and the data modeling and standardization are presented as the main relevant solutions to solve this problem. The second challenge is the realization of an infrastructure to promote the design, implementation and evolution of context-aware systems. For that, a use case is explained in section 3 to show the importance of such a solution. Then, it is proposed to define levels of awareness based on the CAP model of Vanderhaegen (2016) in order to adjust in real time the control of an automated system thanks to an evaluation of the capacities, availability and possibilities of an agent to act (section 4). The last challenge identified by Abowd and Dey (1999) is a discovery of compelling context-aware applications that assist our everyday interactions with ubiquitous computational services. Authors therefore have the idea of creating an intelligent and dynamic interface for identifying peri-information and use CAP factors assessments in real time (section 5). Finally in section 6, a critical discussion is brought to caution future designs of Human-Machine Systems such as Digital Twins (DTs) in a high risk context.

## 2. CONTEXT MANAGEMENT

### 2.1 Definitions

Context can be defined as any information that can be used to characterize the environment or the situation of an entity. An entity can be a person, a place, or a physical or computational object. In Ascone and Vanderhaegen (2022), it has been shown that the elements surrounding a system (the context) are poorly used and considered in its modeling. Similarly to *meta-data* ("*meta*" means "*that encompasses and transcends*" in Greek), this kind of

contextual information can be defined as *peri-data* ("*peri*" means "*that is around*" in Greek). As such, the authors have developed definitions for terms that are used in this paper, as adapted from Pfautz et al. (2006):

- Data: output from a human or machine system that can be used or not in the decision-making process (e.g.: "*the car speed is 57.2km/h*").
- Information: identified input from a human or any system that can be used or not in a decision-making behavior or process (e.g.: "*the speedometer indicates a speed higher than 50km/h*").
- Meta-data: is characteristics or qualifiers of a data (e.g.: if Data is "*the car speed is 57.2km/h*" then a Meta-data could be "*data recorded on 01/01/2023 at 01:01:01:111ms*").
- Meta-information: is characteristics or qualifiers of an Information (e.g.: if Information is "*the speedometer indicates a speed higher than 50km/h*" then a Meta-information could be "*information perceived by a speedometer older than 15 years*").
- Peri-data: data from an auxiliary human, machine or environmental system indirectly linked with the main system (e.g.: a *peri-data* of a human-car driving can be "*the tire/road friction coefficient is 0.3*").
- Peri-information: information from an auxiliary human, machine or environmental system indirectly linked with the main system (e.g.: a *peri-information* of a human-car driving can be "*it rains on the road*").

A solution to bring more reliability into the system could be answered by a peri-consideration and a use of meta and peri data/information. These concepts are already defined in the computer science community as Context-Awareness (Motta et al., 2019), (Perera et al., 2013) and in the human-machine cooperation area as Situation-Awareness (Millot, 2013). Awareness of the system environment described in this paper encompasses these two types of consideration (technologies and humans) in the so-called Overall Situation Awareness.

## 2.2 Capture and Storage

Under uncertainty, understanding and controlling complex environments is only possible by means of information exchange between devices (Çalış Uslu and Firat, 2021). For sure, meta- and peri- information are not always available and it may be challenging to collect them. To make rapid decisions, a network made up of smart devices is needed. In a Holistic Digital Twin architecture, smart handheld devices, mobile phones or other enterprises systems are present and get peri-information which are transferred and updated consecutively into the digital space (Wei, 2021). The model can analyze point-in-time data, historical data, and extract meta-information from these data. To this, additional technologies must be added that allow the capture of machine meta-data (consumption, temperature, speed, or modes of operation) as well as the operator meta-information, such as his/her tasks and work objectives. Finally, human data can be recorded through devices such as an eye tracker, heartbeat recorder, and camera, configured to establish principles of vigilance detection

or emotional recognition. Such systems that are equipped with identification and sensing capabilities are the bridge from the physical to the virtual realm. Indeed, as time goes by, new situations and behaviors that could not be predicted are appearing. These technologies can be efficient ways to achieve a complete and well-designed Digital Twin taking into account each aspect of the system situation, the user behaviors and both surroundings.

The models and architecture of the system become more complex with these new inputs and technologies, which is why a unified data management infrastructure is needed. Data modeling represents the very foundation of the standardization process, providing reliable high-quality data that can be trusted. This data modeling work will lead to a standard for all data and information of the whole system. Similarly to a meta-data standard, a requirement is intended to establish a common understanding of the meaning or semantics of the data, to ensure correct and proper use and interpretation of the data by its owners and users (Řezník et al., 2022). To achieve this common understanding, a number of characteristics or attributes of the data have to be defined (meta-data). Data modeling also enables one to make links between agents and assets. Take the example of "a car in manual driving mode"; to this car is associated an underlying agent, which is "the driver", as well as a larger system which encompasses the two previous ones, which can be called a "driving environment". The principle of standardization will allow links to be created between each agent so that in a given "driving environment" there are one or more "cars" and in each car there is a given "driver". How the data are stored is just as important as how they are captured. If data get lost, misplaced, and the query system is too slow, the use of this meta- and peri-information can bring more harm than good, especially in a high-risk context. Hence the importance of a data management system.

## 3. USE CASE OF A HUMAN-CAR DRIVING SITUATION

Let us start our discussion with a modeling work done in Vanderhaegen (2017) studies and experiments. Driving is a relatively complex Human-Machine System (HMS) with various Human-Machine Interactions (HMI). The realization of a Digital Twin of this system requires one to take into account a model of the vehicle as well as a second one representing the driver and the interactions between both. Firstly, a conceptual model of a human-car driving was established, then all the rules that govern the driving of a vehicle by a human were listed to form a driving model, see Figure 1.

After validation by a panel of 43 car drivers, these rules of human driving behavior are set up in the human model of a Human-Car Digital Model. A DM (Digital Model) is different from a DT by the fact that it has no direct link with a real and physical system (Ascone and Vanderhaegen, 2022). The models can be identical in both configurations but with DM the data are simulated. Simulation tools such as Digital Models can then provide model designer (as human drivers) with pedagogical feedback to support the dissonance control process of a DT (Vanderhaegen, 2021). For example, related to rules R3 and R7 of the Digital

<i>Manual speed control</i>
R1: To control the car speed that is under the sign's speed setpoint → Accelerate
R2: To control the car speed that is over the sign's speed setpoint → Brake
<i>Manual traffic control</i>
R3: The traffic light is green → Do not Brake
R4 : The traffic light is yellow AND The distance is long enough → Brake
R5: The traffic light is yellow AND The distance is too short → Do not Brake
R6: The traffic light is red → Brake
R7: Avoid a frontal obstacle → Brake
<i>Manual steering control</i>
...
<i>Manual warning control</i>
...

Fig. 1. Frame of reference of the human car driving control

Twin model in Figure 1, a new high risk was observed. Indeed, since a tricolor is green, the car driver model will not stop and continue its route (i.e., application of the rule R3). However, the car driver model can decide also to stop before another car in front of them in order to avoid a collision (i.e., application of the rule R7). The application of rules R3 and R7 relates to normal behavior under normal conditions. Such a dynamic situation was simulated by the MissRail Digital Model platform of the Polytechnic University of Hauts-de-France (UPHF, Valenciennes), Figure 2. In the first step, the car moves next to a tram line and behind another car, respecting the safety distance. In the second step, the Human-Car simulation approaches the tricolor signal that is green. Finally, in Step 3, the digital driver stops the car to avoid a frontal collision with another car. However, the digital user stops the car on rail tracks, and then a potential lateral collision between the car and a train can occur.



Fig. 2. Pictures extract from the Missrail Experiment

It should be noted that even models designed by experts and validated by a large panel of experienced users can lead to risky situations in specific conditions. Rule-based models seem to be theoretically efficient and understandable for users, but they do not allow one to take into account all the possible and conceivable situations that can be encountered in our world. Furthermore, the systems to be controlled should no longer be segregated and an all-inclusive design should be established within the design community of Cyber-Physical&Human System. Another difference between DM and DT is the possibility for DT

to adapt themselves and act according to the "whole" environment. One of the characteristics of holistic and inclusive design is then the precious Context Awareness ability. In practice, models rarely require or significantly encourage the inclusion of peri-information and meta-data (Guarino et al., 2009). Peri-information is not always available in the incoming data stream for these models and may need to be obtained separately, either through specific requests or additional computation. Incorporating the proposed Overall Situation Awareness concept in models represents clearly a significant challenge and will allow one to make Digital Twin more inclusive and holistic.

#### 4. PREVIOUS CAP CONCEPT AND IMPROVEMENTS

Regardless of the type of cooperation modelling, zero risk cannot exist in various and uncertain environments. A different way of design consist to add decision making modules to counteract the risky situations (Millot, 2013) . Indeed, it is more difficult to take contextual factors into account upstream the use, i.e. during the design of the model. In that case, it would be necessary to model all the rules including all possible peri-information ; which is almost impossible or at least would make the model totally complex and impossible to manage, recondition or modify. The easiest way to integrate peri-information into the system architecture is still to add a separate decision making module downstream the system model which will allow the risk factors of the situation to be calculated. A such complete system that can update its model and synchronise itself is assimilated to autonomous system such as Holistic Digital Twins (Ascone and Vanderhaegen, 2022).

When the Human-Machine System is an autonomous system, the autonomous model defined by Vanderhaegen (2016) can be used and adapted thanks to the three minimum parameters: system Competence, system Availability and system Possibility/Prescription. The so-called Competence-Availability-Possibility (CAP) model is then proposed to represent the capability of an HMS to act alone and to control conflicts of autonomy in terms of competence, availability and/or possibility. The competence or capacity of an agent to act (human or machine) depends essentially on its designed functions and its use through time (wear, breakdown, breakage...). In terms of availability and the possibility to act, several questions arise in this kind of design. How to measure the availability of an agent (especially when it is about a human)? Then, how do we identify the possibility to act of an agent on a given action? An evaluation of the surroundings (peri-data and peri-information) can be very useful to answer this challenge. Based on the CAP modeling principle, the idea is now to define dynamically levels in terms of capacity, availability and possibility, thanks to an awareness of the internals ("meta") and surroundings ("peri") information of each asset. Therefore, due to the capture of meta-data and the peri-data recorded in the asset environment, it is necessary to define the awareness levels of each of the three parameters (C,A,P) to adjust the control of the whole Cyber-Physical&Human System (Figure 3). An architecture presenting such a device will allow to assess

agents and to assign tasks in real-time according to these evaluation.

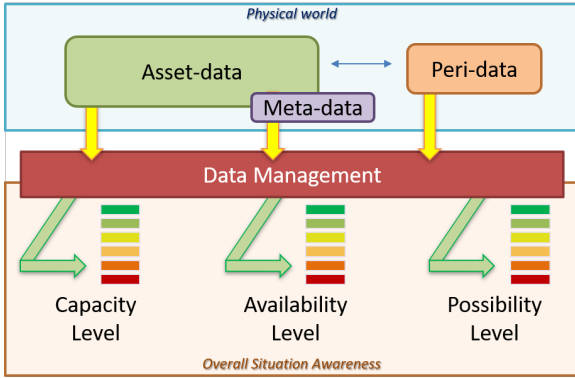


Fig. 3. Overall Situation Awareness Levels Architecture

The old CAP method allowed to assess the collaborative system and to highlight the possible dissonances after an undesired event and in a manual way (by a human). This new architecture will allow a dynamic (automatic and online) evaluation of the 3 parameters in order to set C, A, P levels and define an overall awareness of the situation and its context. For the whole system these three criterion can be calculated dynamically (at each instant  $t$ ).

First of all, a list has to be made with all the factors (data, meta-data, peri-data) and events (information, meta-information, peri-information) that respectively compose and affect the system and subsystems, see table 1. For each factor, a degree or level of importance must be defined, it correspond to the gravity level of an event. and then associated with the criteria it affects.

Table 1. Example of Factors Definition List

Label	Info	Criteria	Degree
F1	info1	C	low or 0.04
F2	info2	A	normal or 0.15
F3	info2	P	high or 0.36
...	...	...	...

Once the list is made, a method of association and calculation of risk must be put in place. A risk factor of occurrence of an event is defined by its occurrence and its severity ( $RF = O * G$ ). Severity or gravity of a factor corresponds to the impact it has on the system (degree column in the previous list). Whether it is a label, as 'high' or 'low', or a numeric value, as a temperature, the value must be normalized and restricted to a given interval. The same is true for its probability of occurrence, so that the product  $RF(t)$  is between 0 and 1. If the  $RF$  value equals 0, it means that there is no influence on the system, in contrast, a value of 1 corresponds to an inability to control the system during that event. A weighted sum of all the factors is then done at each instant  $t$  to obtain the time Overall Situation Awareness ( $OSA$ ) level of the system:

$$OSA(t) = \sum_{n=1}^{N_c} RFc(t) + \sum_{n=1}^{N_a} RFa(t) + \sum_{n=1}^{N_p} RFP(t)$$

Once the structure developed and each weights defined, the last part to achieve is the linkage of factors to data

and information. Periodic or event-triggered, some other devices are then necessary to achieve a complete solution of HMS assessment.

## 5. A COMPLETE CONTEXT AWARENESS SOLUTION

In the previous example, it was the consideration of crossing a railway axis that would have allowed to change the outcome of the scenario. Once captured, this meta-information could have been used to set a larger stopping distance between the two vehicles, thus avoiding this risky situation. Consideration of contextual factors can often appear upstream of the design, during the test phases by simulation, i.e. using the MissRail tool. In each simulation of scenarios, new accidents and new dissonances can be simulated. According to these identified gaps, new rules can be established in the model, such as rule R100: 'If there is no place to pass through a railway axis, then do not pass.' or rule R101: "if there is a railway axis, then Increase the inter-distance by 10 meters.". In more complex models peri-data are fixed and have no flexibility or variability during a scenario. Models are adapted to work in a certain area. More simply, peri-data response times and efficiency can be improved by a real-time update of these data and thanks to a transformation of these previous parameters into real-time variables. There is a real need for dynamic evaluation of CAP levels.

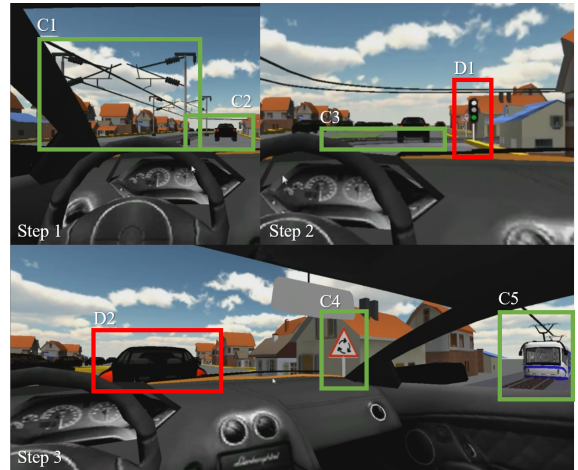


Fig. 4. Pictures extract from the Missrail Experiment with the Context-Identification tool

The example in the following figure shows a system for identifying peri-information in real time through an image recognition process based on artificial intelligence techniques such as Deep Learning (Figure 4). Work such as Maaloul (2018), Lebrun et al. (2013), or Habib et al. (2021) can help to realize such a system. The figure describes the same scenario as in section 3 "use case". The scenario is also split into images reflecting the 3 steps, but on which are identified in "green" the new contextual information that had not previously been detected without the aid-system (unlike those in "red" that were). In Step 1, the system enable the identification of the tram infrastructure (C1) and a busy car traffic in the background (C2). These peri-information can be used by the intelligent system to notice the user, make him/her more vigilant and so



## 6. DISCUSSIONS

increase its availability. But for the purposes of this article, such a tool can be used to detect objects, signs, etc., to finally affect the 'Occurrence' part of the respective risk factor  $RF$ . In Step 2 of Figure 4, 'the traffic light is green' (D1) was an information already perceived by the Digital Twin, but the system had not given importance to the ground and the presence of rail on it (C3). Preventing the car from getting on the tracks too quickly would have increased the vehicle's possibility to cope with the arrival of a tram. Another peripheral information, such as C4 (the roundabout sign), provides more information to the driver and affects his driving choices. For example, the driver should have anticipated and looked to see if the traffic in the roundabout would have allowed him to pass and not end up in that situation (D2: to avoid a frontal collision with another car, the user stops the car). To all this, one could add the identification of peri-information such as 'collision with an imminent tram' and 'no vehicle/object behind', which, when combined, would have allowed one to drive in reverse and avoid the collision.

Authors, think also to use other peripheral devices like camera, to observe and measure the availability of the driver during the driving phase. The concept of eye-tracking already makes it proofs in academic and industrial areas and allow to diagnose the driver attention (Carr and Grover, 2020), (Bendjoudi et al., 2020). We can push the design to it extreme and realize a complex human model of the driver. It is important to mention in this type of model that the orders of magnitude of human parameters are relatively variable in literature (La Delfa et al., 2021). If these parameters are so changeable, it is because they depend on the human being and other external factors. In a holistic system design with Context Awareness and Meta-Information on the human being, there should not be so many parameters but rather variables that are driven by factors such as capabilities or availability. This can be achieved through human data capture devices and on a register of user's meta-data and meta-information.

To complete the whole assessment system, a minimalist interface has been developed to display the results of the proposed C,A,P level technique (Figure 5).

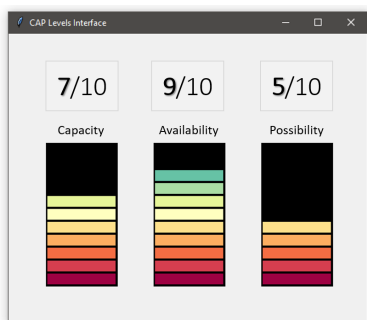


Fig. 5. Context Awareness Levels Interface

The interface is easy to implement on a car dashboard, for instance. Tests and experiments are still to be done in order to confirm on a large public the necessity of a such interface in future Human-Machine Systems.

In the holistic architecture, taking a maximum of data into account makes it possible to define an integral awareness of the situation of an agent (Overall Situation Awareness). The capacity factor can be influenced by many items (Vanderhaegen, 2012). For example, the capacity of a human to perform a specific task can be assessed by integrating personal data into the models. Physical factors such as height, weight, corpulence (etc.) define operators' capacity to perform certain tasks (i.e., "grabbing an object at a height"). In hospitals, medical records are centralised and allow for more accurate and rapid diagnosis of a patient (Wei, 2021). Taking into account an operator's disability (physical or psycho-motor) makes it possible to evaluate more effectively a human's ability to perform a given task. Age is also a good factor to evaluate the reactivity of humans. All this requires the personification of human models, but also raises questions about the ethics of this data. Capacity of a machine is easier to capture because they are linked to design information, maintenance, damage (i.e., "capacity of a machine to pack 500 biscuits per hour ; feasible or not?"). Then, the availability factor can be assessed using different techniques. Availability can be simply answered by the question "Is the machine or human available to do that task?". The availability of a human or a machine to do a specific task can be done thanks to a camera to see if the operator is not work overloaded ("he/she is already doing something else") or thanks to asset meta- and peri- data, for instance, the state of machines' semaphores and machines availability information (maintenance state or process mode). Semaphores can be described as counters used to ensure synchronization between processes for shared resources. Finally, the prescription of an asset to perform a task can also be defined as the time at which an obligation cannot be continued. Therefore, it is a question of the notion of the possibility of doing a specific thing. For example, the possibility of a human to enter in a certain zone, or the permissions and requirements to hold an object (due to the temperature or if its a too much delicate thing). In terms of machines, it is more an authorization of an action (i.e., "Is the car allowed to activate the horn by itself in a certain situation?").

Unfortunately, it seems that simple rule-based systems are no longer sufficient on their own to maintain a requirement such as safety in decision-making of risky systems. There are artificial neural networks and other machine learning techniques that enable Artificial Intelligence by implementing an algorithm that trains a machine on how to learn by itself to adapt upcoming changes without human intervention. In that sense, these new rules can also be created and used by the system itself completely automatically, without the need for designer confirmation. One could even imagine having a very simple model and training it via simulations and by defining the operating, safety, comfort, economic (etc.) objectives alone. With this method, it is possible to carry out a large number of tests to identify design flaws and improve the design before deployment. However, the diversity of scenarios is limited only by the imagination of those who create them. That means, it is highly impossible to model all possible risk scenarios and therefore the model may not know what to do in an unknown situation. Whatever the performance of

such techniques, there is always a doubt about the trust that can be placed in them, especially for system control. In fact, the notion of "without human intervention" instills fear in all communities, at the ethical, political, or safety level (Anderson, 2005).

## 7. CONCLUSION

In the present paper, authors brought solutions that can improve models of Human-Machine Systems, such as the use of human data, meta-data and peri-data. They defined a state of the Context Awareness around the machine and the human that can be used in the decision making or even models. This principle is reminiscent to the Holistic Framework where a decision can be made only if the context of the process and the situation of the operator in it are well known. The Context Awareness impacts on the possibilities and availability of an agent to act. Meta-information is more present to modify the ability of an asset to act on a certain task. Additional systems as Decision Maker are efficient to keep safe systems. The proposed decision technique can also be augmented by a tool which will enable the identification of human behaviors and feelings such as the works of Jegham et al. (2018) or Bendjoudi et al. (2020). The human meta-data recorded and the car meta-information available can then allow the variation of skill and capacity level. In general, it is certain that the vehicle's maintenance booklet will influence the capacity level of the asset, as well as the history of accidents that can modify the car's functions. CAP levels can be a good way to take all factors into account and sum up the context and situation states of a system in operation. With all these techniques combined, it is certain that a significant number of peri-information and human-information will be captured. They can then be used by the decision making system directly or via an interface for the user to be defined. Taking into account the environment and context in visual representations of system environments will improve realism, reliability, and situational awareness on the user side too. These elements are added to the models to achieve the overall holistic architecture for Digital Twins.

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