Enabling Industry 4.0 approach in Multi-Messenger Astronomy experiments

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Abstract. Industry 4.0, based on digitisation and in tight connection to the Internet of the Thing, represents a reference paradigm that can significantly improve the efficiency and productivity in the construction of large experimental infrastructures for science. In this work we propose a methodology based on integrated hybrid systems which combine digital twins of physical phenomena and hardware components with parts of real apparatuses made of sensors, actuators and software implementations. The peculiarity of the proposed methodology is the orchestration approach which leverages the concept of Virtual Commissioning which allows the design, test and realisation of an infrastructure by means of synergic advancements of virtual representation and the actual implementation.

1 Introduction

Large-Scale Scientific Infrastructure (LSSI) is the go-to for cutting-edge astronomy and high-energy physics. Such research infrastructure is made up of a number of components, including construction facilities, engineering systems, and highly sophisticated control and measurement equipment. These systems must meet strict standards in terms of operational complexity and precision. Furthermore, the projects related to LSSIs must be prepared to handle the high installation and operating costs, environmental sensitivity, and data loss risks inherent to long-term, unique experiments [1].

In response to the aforementioned challenges, Virtual Commissioning (VC) has been developed as a solution. *Virtual commissioning* can be described as "the act of setting up, testing, and validating a system's design and operation in a virtual environment on a computer" [2]. In essence, it comprises the utilisation of software for the testing and validation of control, communications, condition monitoring, and physical phenomena data processing software, preceding the actual construction of the physical infrastructure. This is undertaken to ensure that the software and hardware are correctly configured and will operate as intended once the system is deployed in the real world. By conducting this process during both the development and the construction phases of a project, the majority of the commissioning tasks can be removed from the critical path. In general, for any high-energy Physics and Astro-Physics experiments with large installations, such as km^3-size neutrino telescopes, gravitational waves interferometers, ground based Cherenkov telescope arrays, as well as

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satellite experiments, due to their complexity, a commissioning phase is still necessary to verify that the system functions as intended. However, the majority of potential problems can be identified and resolved earlier in the process by identifying and addressing software and hardware issues at an earlier stage. The concept of *Industry 4.0* [2], as well as that one of *Digital Twin* (DT) [3], are a concepts closely related to VC. A DT, in short, is defined as a contextualised software model of a real-world object. This leads to the definition of the real space and virtual space, along with the flow of data and information from the real to the virtual space and vice versa. A key tenet of the DT is the interconnection of two systems: the physical system, which has always existed, and the virtual system, which contains all pertinent data regarding the physical system. This interconnection generates a mirror effect between the virtual and real-world spaces, establishing a dynamic relationship that persists throughout the four main phases of a product's life cycle: design, production, operation (including maintenance and support) and disposal. This framework enables the implementation of virtual commissioning, condition monitoring and predictive maintenance via the digital twin. The above-described overall framework is depicted in Figure 1.

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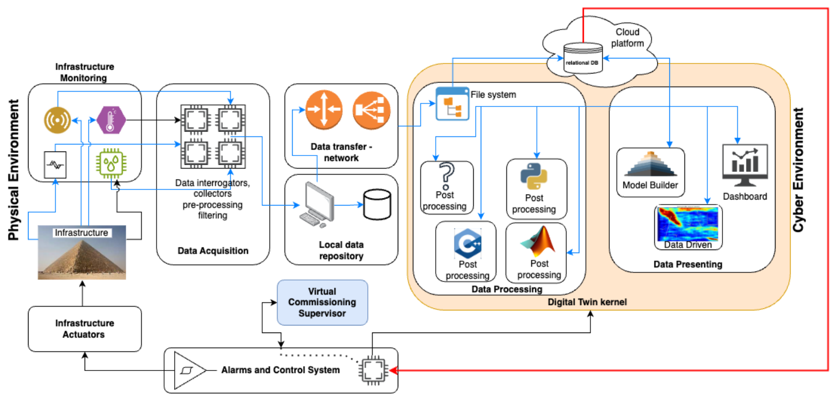

Figure 1. Overall framework where real hardware, the ancillary resources (i.e. computing and networking infrastructures) and a Digital Twins based ecosystem coexist. Inspired by [4].

2 Layered Framework for combining Physical and Cyber-systems IN LSSI

The literature has paid particular attention to the use of VC operations during project phases. Nowadays it is true for Industry 4.0, and will be even more in the future for Industry 5.0. This has the effect of influencing the evolution of the project itself. In this contribute we propose an approach leveraging the above mentioned Cyber-Physical framework, which is implementable starting from a realistic use-case. At first instance, we consider a limited part of some large infrastructure commonly used in many detectors, i.e. the Field Programmable Gate Array (FPGA) firmware driving the data-acquisition of some electronic boards connected to various instruments and sensors, such as compasses, temperature or pressure meters, acoustic environmental devices, such as hydrophones or piezo sensors, LVDT actuators or position sensing detectors.

One ambition of this proposal is to introduce a standardised layered framework which adheres to the ISO 23247 Digital Twin Manufacturing Framework ([5] and citations therein). This provides a reference architecture that is both domain- and entity-based, thereby facilitating the implementation of digital twins across a range of manufacturing applications. The

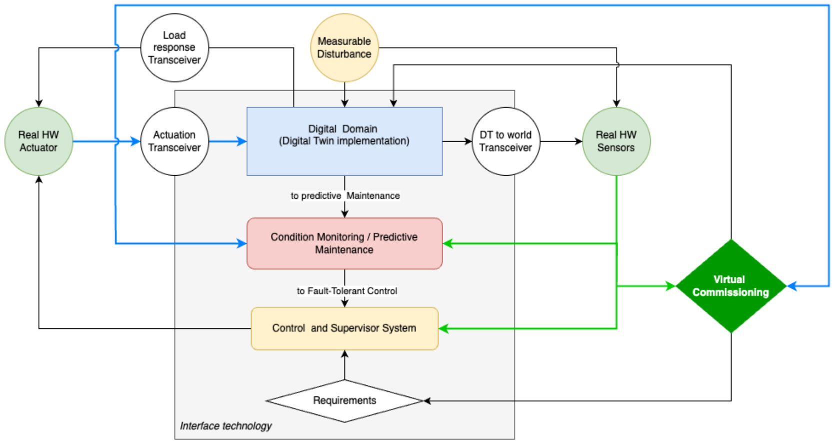

Figure 2. Overall Framework for Virtual Commissioning, where software elements (in the grey box) are interfaced to real hardware components (hardware-in-the-loop), under the orchestration of a VC supervisor.

term *domains* is employed to describe the abstract physical manifestations of components and constituents at various aggregation levels, without consideration of their actual metrics, morphology, or materialisation. The domains classify functions according to their respective areas of responsibility, which are typically divided into four categories: (1) the physical domain, (2) digital domain (or core domain), (3) the cross-space domain (or data collection and device control domain) and (4) the user domain. A logical grouping of tasks and functions is associated with each domain. These are performed by functional entities and sub-entities operating at a lower level. The domain-based DT framework is utilised to facilitate the design and development phase of the project. Each domain can be readily associated with a work package or unit case in the research project.

The real implementation (e.g. the electronic board with some FPGA and all the connected device) is the physical domain. It is virtualised into a DT which defines the range of the digital domain. The FPGA firmware, which is usually built from a gateware and some embedded software, is still realised with the usual development environments (Vivado/ISE Design Suite for Xilinx FPGA or Quartus for Altera FPGA) but is now implemented on FPGA simulators such as ModelSim, GHDL and the like, according to the chosen FPGA model. This represents the core of the Physical Phenomenon DT. On the sidelines is the rest of the infrastructure, from the printed-circuit board, the chosen peripherals and the connected devices. The interfaces between the FPGA simulator and the sensors (eg. I2C buses, UART ports etc.) can be simulated exploiting dedicated products provided by the FPGA vendors or in a custom mode via development contexts like SystemC. Finally the sensors and instruments can be developed software-wise with the usual programming languages like C/C++. This represent the modelling core of the Cyber part. The VC is then realised by operating the DT according to a huge variety of configurations, which can characterise the temperature, the pressure or stress of the sensors, the signal frequency/throughput from the simulated instruments etc. The advantage of the VC is that it is easily possible to implement situations that may be difficult, improbable, costly and hazardous to implement in a real-world context, but that can be essential in detecting some possible system flaws. The physical and digital domains are interconnected via the cross-space domain, which allows to implement the necessary mutual feed-backs between the real-world installation and its DT. This can be achieved via specific physical links and API between the actual electronic boards and the computing resources where the DT is running, for pushing configurations from the Cyber part to the Physical one, and vice-versa, or more simply allowing the manual transfer of some system-parameterisations, possibly optimised in the digital domain or found faulty in the physical domain. Note that some of the peripheral sensors or instruments previously introduced as a complimentary virtual environment to the Physical Phenomenon can be substituted by real devices properly interfaced with some API. In this case we talk of *hardware in the loop*. The latter case is sketched in Figure 2, where a DT and some hardware-in-the-loop systems are embedded in a unique framework combining and coordinating Real and Cyber systems, exploiting data (acquisition, processing and visualisation), control (VC, alert/actuation). The proposed framework allows for the execution of a variety of operations, including: (a) open-loop operations: Condition Monitoring, Predictive Maintenance, and Virtual Commissioning/Cyber Security; (b) closed loop operations: System and control system reconfiguration, fault-tolerant control, real commissioning.

3 Outlook

In conclusion, the interfaces between the processing blocks can be developed with the objective of implementing a virtual commissioning process, which aims at optimising the phases and integration of the infrastructure development. The proposed Cyber-Physical ecosystem, which is here limited to a single FPGA context, is naturally expandable to include other parts and components of the research infrastructure. For the next-generation detectors in the field of Multi-Messenger Astronomy, still under design or under construction, it would be very effective to address the DTs implementation and exploitation to study the reliability of the detection elements under various critical situations: sea-current induced vortex which can mechanically stress submarine detection units of KM3NeT [6]; noise transients from sensor data occurring upon different environmental conditions which can affect the Einstein Telescope interferometer [7] as well the readout apparatuses of the CTAO mirrors [8]. These perspectives were treated among the subjects of a project submitted to the call HORIZON-INFRA-2024-TECH-01.

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