RHDTO Specification

An Ontology for the Implementation of Reactive Heritage Digital Twins

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Based on a preliminary and partial work by a wider team of researchers.

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Introduction

Scope

This document presents the RHDT Ontology (RHDTO), a model for cultural heritage based on the concept of digital twin. The ontology is a compatible extension of the CIDOC CRM ISO standard for cultural heritage documentation, and is primarily conceived as a conceptual tool to capture the dual nature of cultural heritage, both tangible and intangible, and to provide, through specific classes and properties, a mechanism for dynamically documenting and analyzing their mutual relationships. It is also designed to model their digital counterparts and the mechanisms that make them interconnected and interoperable, fostering the implementation of complex digital twin systems. The ontology also provides the conceptual tools to describe the reactivity that digital twins are able to deploy for cultural heritage documentation and preservation, by including the semantic description of sensors, signals, actuators and all of the process of interacting with real world objects.

Digital Twins and Cultural Heritage

The RHDT Ontology is founded on the concept of digital twin, a paradigm born in the industrial field, mainly with the aim to test components and devices, and to simulate the real behaviour of complex appliances in a digital way. Then, digital twins made their way in machinery control applications, by using sensors surveying the behaviour of a device and sending an alert when an anomalous value is measured, or directly activating specific components to return to a normal condition. This kind of application required the use of simulation processes within the model, which were eventually incorporated in the concept of digital twin. Nowadays, this concept is sometimes present as a generic term to designate a digitised model of real artefacts or, more specifically, a structured information system about reality. Also, regulatory authorities, such as the European Commission, are using this terminology nowadays.

Digital twins have become extensively used among others in mechanical engineering, architecture and especially in the building industry, where they belong to the BIM approach. The idea of introducing digital twins in land planning and built environment activities dates back to the Cambridge National Digital Twin project, which stated general, with the the Gemini Principles, the general criteria for their application in this domain[1].

As concerns cultural heritage, the term digital twin made its appearance in reference to digitised 3D models of heritage artefacts as a synonym of digital replica, suggesting an original literary rather than technical use of the term. The first applications of 3D visualisation in cultural heritage date back to the last decade of the 20th century, especially in archaeology, and were motivated by the need to illustrate the supposed pristine appearance of remains, replacing drawings and maquettes previously used for this purpose with visual reconstructions of the past. A similar approach rapidly extended to document the shape of artefacts, monuments, and sites and has now produced a huge amount of heritage 3D models of extremely different quality and detail. Looking at heritage assets in 3D rather than by 2D images has become a straightforward practice, although still needing more work.

3D models have also been used to document aspects of intangible heritage, but they are usually less suitable as the starting point of the related documentation which includes stories, traditions, and

[1] See Bolton, A.; Lorraine, B.; Dabson, I.; Enzer, M.; Evans, M.; Fenemore, T.; Harradence, F.; Keaney, E.; Kemp, A.; Luck, A.; et al. The Gemini Principles: Guiding Values for the National Digital Twin and Information Management Framework, 2018. Available online: https://www.cdbb.cam.ac.uk/system/files/documents/TheGeminiPrinciples.pdf.

other immaterial content is very often unrelated to the shape. In some other applications, the additional information concerning, for example, materials used in different parts or conservation interventions has been attached as a text to the 3D model or to some of its regions. Although availing a completely different 3D technology, similar applications have been developed adopting a CAD approach to the creation of the 3D model. In this case, the heritage-related documentation is managed by extending an existing information system, called BIM (Built Information Modelling), widely used in the building industry to specify information about materials, services, and processes concerning the construction of a new built asset. Since the architecture domain has a close similarity with cultural heritage, such proximity has promoted the development of HBIM, i.e. Heritage BIM, which incorporates the BIM approach enriching it with additional classes pertaining to the heritage domain, but still within a flat data system. Nevertheless, the heritage domain requires much greater attention on how information is organised, an essential step before continuing to computational modelling that simulates real-world processes, the primary focus of most industrial digital twins.

All the previously mentioned approaches face a fundamental issue: starting with a 3D model as the core of the documentation, which complicates data processing beyond individual assets. In time, it has become evident that taking into account only the shape of heritage assets is not sufficient for advanced model use, both in research and in practice, since this approach hinders efficient comparisons and searches, as the information is not organized in a way that supports advanced knowledge organisation technologies. Any serious use requires background documentation which needs to be stored, linked to the 3D model, and made available for inspection. A more effective method involves a semantic approach, where heritage documentation is structured into classes interconnected by properties, enabling complex queries and comprehensive data management. This system allows for better organization and reuse of research data, aligning with FAIR principles by ensuring findability, accessibility, interoperability, and reusability.

In this context, ontologies serve as essential tools for representing cultural heritage and articulating the interconnected knowledge network surrounding it. They provide a flexible conceptual framework that organizes information, making it accessible and interpretable by both humans and advanced computer systems. The use of standardized vocabularies ensures data consistency and uniformity, which is crucial for enabling interoperability across different systems and platforms, thus facilitating information exchange among institutions involved in heritage conservation and promotion. Owing to these features and their ability to efficiently manage aggregated documentation, ontologies can act as the "engine" driving cultural digital twins throughout their operational phases.

In cultural heritage, CIDOC CRM holds a fundamental role in the current landscape of ontologies by offering a versatile framework for the integration, mediation, and exchange of cultural heritage information. Its relevance is particularly notable in architecture, a field characterized by complex and rich data. The event-based CRM paradigm facilitates the representation of chronological data, functional aspects, restoration activities, and the evolution of construction styles and techniques, allowing for a dynamic and diachronic analysis of the acquired data. Extensions such as CRMba and CRMarchaeo enable the detailed modeling of historic buildings, urban structures, and archaeological contexts, transforming them into structured semantic descriptions. These features justify the choice of adopting CIDOC CRM's philosophy for developing our ontological model, given the robustness it provides at every stage of knowledge modeling.

For these reasons we decided to develop an ontology that manages the vast complexity of this information and that lies at the very heart of the cultural digital twin. Data organisation based on semantics, in fact, allowed us to define a new digital twin paradigm, the Heritage Digital Twin (HDT), intended as the complex of all available digital information concerning a (real world) heritage asset, either movable (e.g., museum exhibits), immovable (e.g., monuments and sites), or even intangible (e.g., traditions). In the resulting ontology, all of the data, such as reports, documents, datasets, and visual representations (2D, 3D, or 4D), or any other related digital data, are linked with each other within the HDT by appropriate properties.

The ontology is also capable of modelling functional aspects of the operational life of digital twins, typically consisting in the interaction with reality and the continuous interchange of information and process activation with the real world. This is the “reactivity” embedded in the digital twin concept, consisting in responsivity to inputs coming from real world objects and evnironments, and the capacity to produce corresponding outputs and real-world actions. This way, digital twins can mirror heritage assets which are immersed in a continuous changing landscape, are affected by phenomena happening in it, and with their own changes, contribute to compose their evolution.

Thus, our ontology also provides tool to model the functionalities that allow to describe the reactivity of digital twins used for cultural heritage documentation by including the semantic description of devices, signals and all the other interactions between the real world and the digital world, and the processes that get data from the real world via sensors, process such input in the virtual world using the features and data of the virtual models and, according to the results, update the virtual models and trigger real world actions via actuators. The resulting model is the Reactive Heritage Digital Twin Ontology (RHDTO), which we present in this document.

Naming Conventions

RHDTO is based on the CIDOC CRM and its ecosystem, using whenever possible, the classes and properties of the CIDOC CRM and its extensions to model digital twin features, and defining new ones only to describe more specific concepts such as cultural entities, intangible values, 3D models, which do not find an exact match in the CIDOC CRM. In any case, as far as possible, we have always tried to derive the new entities from those of the CIDOC CRM family in order to keep our model completely compatible, consistent and aligned with it.

All the entities of RHDTO are provided with a name and an identifier constructed according to the conventions used in the CIDOC CRM model. For classes, the identifier consists of the letters HC followed by a number. Resulting properties were also given a name and an identifier, constructed according to the same conventions. This identifier consists of the letters HP followed by a number, which in turn is followed by the letter “i” every time the property is mentioned “backwards”, i.e., from target to domain (inverse link).

The ontological models of the CIDOC CRM ecosystem used to build RHDTO, their version, the letters to identify their classes and properties and the namespaces (prefixes) used to indicate them throughout this document are reported in Table 1 below.

Model	Version	Prefix	Description	Classes prefix	Properties prefix
CIDOC CRM	6.2.1	crm	A formal ontology for modelling Cultural Heritage information	E	P
CRMsci	1.2.6	crmsci	The scientific observation model	S	O
CRMdig	3.2	crmdig	Model for provenance metadata	D	L
CRMpe	3.1.2	crmpe	The PARTHENOS Entities model	PE	PP

CRMinf	0.10.1	crminf	An Extension of CIDOC-CRM to support argumentation	I	J
CRMba	1.4	crmba	An extension of CIDOC CRM to support buildings archaeology documentation	B	BP
FRBRoo	2.4	frbr	Functional requirements for bibliographic records	F	R
NOnt	1.0	nont	The MINGEI Narrative Ontology	nont	nont

Table 1. Ontological models used to build the RHDTO model.

RHDTO Relevant Concepts

As already noted, RHDTO is designed to capture the dual nature of cultural heritage, encompassing both tangible and intangible dimensions, as well as the cultural events that shape the history of cultural entities. It provides dedicated classes and properties for the dynamic documentation and analysis of these interactions. Additionally, RHDTO plays a central role in structuring data for documenting digital twin systems, knowledge bases, and related platforms. By being machine-readable and actionable, RHDTO serves as an internal "language" within the digital twin system, facilitating seamless communication among its diverse digital components.

RHDTO relies on the classes and properties of CIDOC CRM ecosystem to represent widely recognized entities such as places, agents, physical objects, events, and temporal elements, thereby supporting high-level interoperability across various domains. Furthermore, it introduces new classes and properties to describe more specialized concepts, including digital twins, cultural entities, and 3D models, which lack direct equivalents within the CRM framework. This ensures comprehensive modeling capabilities for complex cultural heritage documentation.

In the sections below and in Figure 1 we illustrate the main cultural concepts modeled by the RHDTO ontology and the related semantic entities used to describe their nature and function.

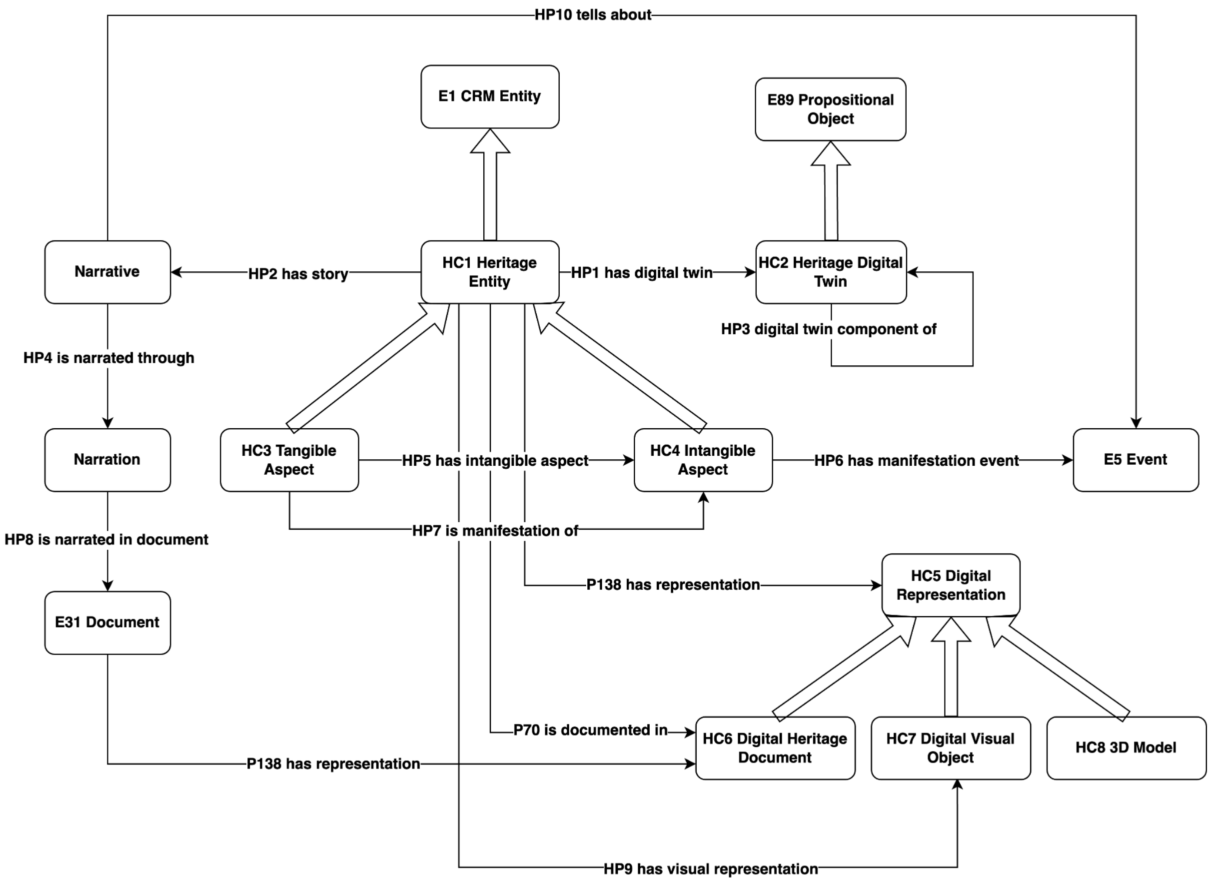

Figure 1: General overview of the main classes and properties of the RHDTO model.

Heritage and Entities and Documentation

The root class of RHDTO is *HC1 Heritage Entity*, a subclass of *crm:E1 CRM Entity* designed to represent tangible and intangible entities valued for their societal, knowledge, or cultural contributions. It is used to model various assets, such as physical objects, digital entities, or cultural events, describing their characteristics across space and time. Its *HC3 Tangible Entity* subclass*,* serves instead to more specifically describe tangible, material entities from the real world, both movable (e.g., cultural objects) and immovable (e.g., monuments and buildings). All these entities may also have intangible aspects, which is captured through the *HP5 has intangible aspect* property, pointing to *HC4 Intangible Aspects*, another subclass of *HC1* designed to encompass cultural events, traditions, and practices that hold significant social, historical, and cultural value, including a wide range of intangible heritage, such as rituals, customs, performances, and expressions, as well as memories and oral traditions related to important events, objects, and individuals.

Other classes in RHDTO are used to model the digital documentation related to heritage entities, encompassing 3D models (rendered through the dedicated *HC8 3D Model* class), images, other audio–visual mediums (modelled using the *HC7 Digital Visual Object* class), as well as textual information made available in digital format (represented by means of the *HC6 Digital Heritage Document* class).

Heritage Digital Twins

Heritage Digital Twins of cultural entities are rendered in RHDTO by means of the class *HC2 Digital Twin* used to organize and connect the digital information available in a given system and pertaining to an *HC1 Heritage Entity*, including digital representations and information of the effects of events that influenced or/and are related in any way to its state and activities (e.g., restorations, conservations, etc.) carried out on it. The *HC2* class semantically represents the way in which the Heritage Digital Twin is implemented and the building blocks through which it operates. In addition to those inherited from the CRM, RHDTO also provides other properties, such as *HP1 is digital twin of*, linking a heritage entity (*HC1*) with its digital twin (*HC2*).

Events

To model cultural events, traditions and practices, typical of the intangible heritage, we use the *HC4 Intangible Aspect* class, linking its instances to instances of *HC3 Tangible Entity* class by means of the property *HP5 has intangible aspect*. While all tangible heritage has always an intangible aspect, intangible heritage does not necessarily have a tangible aspect. Instances of *HC4 Intangible Aspect* describe generic (template) events such as the *Palio di Siena* and not the individual occurrences of the *Palio*. The actual individual occurrences can be modelled as instances of *crm:E5 Event*, and property *crm:P129 is about* may be used to link an individual Event (*E5*) to the generic description of the cultural heritage event (*HC4*), such as the *Palio di Siena* race of the present year (*E5*) which is about (*crm:P129*) the *Palio* tradition (*HC4*). Nevertheless, it was important to define a property to specify this special link between the *HC4 Intangible Aspect* and its punctual manifestations. This property is *HP6 has manifestation event*. The following is an example of this kind of modelling:

- The *Palio di Siena* (*HC1 Heritage Entity*), is a horse race (*HC4 Intangible Aspect*) that is held twice each year, on 2 July and 16 August, in Siena, Italy (*crm:E53 Place*). Ten horses and riders (*crm:E39 Actor*), represent ten of the seventeen *contrade* (*crm:E74 Group*), or city wards.

- The historical horse race *Palio di Siena* (*HC4 Intangible Aspect*) was held again (*crm:E5 Event*) on 17/8/2022 (*crm:E52 Time-Span*) after a two-year pause because of the COVID-19 pandemic. The winner was jockey Giovanni Atzeni (*crm:E39 Actor*).

For events and activities that are not strictly "cultural" and therefore fall outside the immediate scope of *HC4 Intangible Entity*, but which in any case concern, affect and remain somehow connected to the various cultural entities, the *crm:E5 Event* class can be used instead. These are activities like conservation, restoration, reconstruction, and natural events like earthquakes and floods. The type of events for which instances of *crm:E5* are used can be specified by means of the *crm:P2 has type* property. Open vocabularies, containing the most common descriptions of these cultural heritage activities, can be defined and released within the ontology to be used in combination with the above-mentioned *crm:P2* property for a more standardized and complete description.

Conditions and states

An important information about heritage assets is their condition state. In the CRM this is documented using the pattern *crm:E3 Condition State → crm:P2 has type → crm:E55 Type*, choosing instance of the latter in a vocabulary of possible states. If this way of assessing the state of an asset seems too generic, a more precise solution is offered by *crm:E14 Condition Assessment* class. This is the activity dedicated to the evaluation of the condition, and its outcome is a report about the condition. For example, a paper titled "Three-Dimensional Creep Analyses of The Leaning Tower of Pisa" on the condition of the Pisa leaning tower was published in 1997 by Dryden and Wilson. This fact can be expressed as follows:

- The "Analysis on Pisa Tower" (*crm:E14 Condition Assessment*) in 1997 was carried out by (*crm:P14 carried out by*) "Dryden & Wilson" (*crm:E39 Actor*) in (*crm:P4 has time span*) 1997 (*crm:E52 Time-Span*). It is documented (*crm:P70 is documents in*) in the document "Three-Dimensional Creep Analyses of The Leaning Tower of Pisa" (*crm:E31 Document*).

Stories and Storytellings

In RHDTO, stories are considered as accounts of facts about a certain Heritage Entity, including (but not limited to) descriptions based on documents and on their interpretation. Stories are an integral aspect of the framework of a Heritage Entity (and thus, of its Digital Twin) since they contribute to the construction of its intangible part as they may make it more understandable, interesting, and attractive for the public. A story can be seen as the core of a series of facts and how they happened, as for example the story of the Knossos Palace and its discovery by Arthur Evans or the story of Falconry over the centuries. From a conceptual point of view, a story is equivalent to the concept of narrative, i.e., "a story as it happened in reality or in fiction", as defined in the Narrative Ontology (NOnt) of the MINGEI project[2].

Since this definition is perfectly suited to our concept of story, and furthermore, given that the *Narrative* class in the Narrative Ontology is a subclass of *crm:E73 Information Object* of CIDOC CRM, which provides it an additional level of formal compatibility, this class will be used in our model as it is. A storytelling, instead, is considered in our model as the way in which the facts composing a story are actually narrated, presented and disseminated. Storytellings, in fact, comprise social and cultural activities of telling, writing and disseminating stories, for the purpose of education, cultural preservation or entertainment, both in oral form and by means of simple or sophisticated techniques aimed at making the narration of a story effective. An example of storytelling is how the history of Falconry is narrated in *De Arte Venandi Cum Avibus* treatise by the Holy Roman Emperor Frederick II.

From a conceptual point of view, a result of storytelling can be seen as equivalent to the concept of narration, which in the Narrative Ontology "represents the narration of a narrative, i.e. an individual work that tells the events of the narrative through some form of media (text, video, audio, etc.)". There can be many narrations of the same story, focusing on different aspects of the *fabula*, or presenting events in a different order. In the Mingei Narrative Ontology, *Narration* is a subclass of *frbr:F14 Individual Work* of the FRBRoo Ontology, another extension of CIDOC CRM. Since also in this case, as for the story, we have verified the perfect conceptual and formal overlap of this class with our idea of storytelling, the Narration class will also be used in our model as it is.

Reactive Components

[2] https://www.mingei-project.eu. Narrative Ontology documentation is available at: https://dlnarratives.eu/ontology/.

A digital twin interacts with the external world it aims to replicate through a physical devices that serve as the bridge between the physical and digital world, enabling the digital twin to both monitor and influence its real-world counterpart. In particular, sensors are devices, modules, machines or subsystems able to produce output signals for the purpose of detecting physical phenomena happening in the real world. A sensor can detect events or changes in its environment and send the information to an actuator, which automatically activates some action if required according to built-in criteria.

Very simple everyday examples are thermostats, which combine a temperature sensor and an actuator switching off or on an air conditioner if the temperature is within or outside a pre-selected range. The automated action may be very simple, such as the switching on/off of a warning red light in a car fuel gauge or an anti-theft alarm which detects the interruption of an electrical circuit due to the opening of a house front door and activates an alarm siren. The latter case may also consist of a movement detector (the sensor) that sends a signal to the siren actuator.

In general, the model of the overall action encompasses several steps and may consist of:

- A sensor: measuring one (or more) physical quantity—in the above examples, they, respectively, are the temperature, the quantity of fuel in the car tank, and the amount of infrared radiation for an anti-theft movement sensor—and forwarding the measure(s) to a decider.
- A decider: comparing the sensor measurement with pre-set decision rules and deciding if some action needs to be activated. In the above examples, for the thermostat, the decision is based on a threshold, a limit temperature, and the required action is switching the air conditioning on/off; for the fuel gauge, the threshold is a minimum acceptable quantity of it, and the action is switching on the red warning light in the car dashboard; and for the anti-theft system, the action involves determining if the size of the intruder according to the infrared size is comparable with a human or is smaller, such as a cat. If the sensor signal falls in the alarm range, the decider sends an activation signal to the actuator. The decision rules will often be much more complex and imply different actions according to the values measured by the sensor.
- An actuator: when authorised by the decider, it commands actions in the real world, e.g., switching some device on or off, such as the air conditioning system, the car red warning light, and the alarm siren. The action may be programmed to result in something more complex than a simple “Do”; in this case, we may logically split such a complex actuator into different elementary actuators. For example, an anti-theft actuator may command different actions such as “activate the siren” and “call police”; thus, it corresponds to two elementary actuators.

In simple cases, the decider is included either in the sensor or in the actuator, frequently in the latter as in the above examples. It is however a logical functionality different from the device, and thus, we will keep it separate from both.

The logic of the sensor–decider–actuator system is often hard-coded in the electronics of the devices, especially for simple ones, but there is also a strong tendency towards soft-coding to support its integration with other smart devices and enable remote control via wi-fi and the internet. This has led to an increase in the purely digital component, which facilitates the inclusion of this system in a digital twin framework. In any case, both the sensor and the actuator are placed in the real world, so they do not belong to the digital twin but should be included in the overall semantic description of the whole system. The decision process may be very simple, as in the above examples, or very complicated when several factors must be taken into account, requiring processing and possibly, in a forthcoming future, an AI-based decision process.

Sensors

In ontological terms, a sensor can be defined as a digital device placed on physical objects or in specific locations intended to measure and collect data about them, process it, and transmit it to the digital twin system for analysis and further processing. Building upon this general definition, RHDTO provides the *HC9 Sensor* class, specialising the *crmdig:D8 Digital Device* of CRMdig, a general class aimed at describing instances of material items capable of processing or producing digital data.

The positioning of a sensor on a cultural object can be modelled using the *HP15 is positioned on* property, allowing for the representation of the spatial relationship established between the object to be monitored (*HC3 Tangible Entity*) and the sensor placed on it. For sensors positioned in a space adjacent to the cultural object, we can use the *crm:P55 has current location* property, connecting a sensor to the instance of *crm:E53 Place* where the monitored object is currently located to indicate that both of these physical entities share the same space.

During its operational lifecycle, a sensor can assume a particular status representing its condition at a given time, an aspect can be modelled using the *crm:E3 Condition State*. Instances of this class enable the description of sensor states (such as on/off, operational/non-operational) and operation modes, reporting any faults or errors, as well as any maintenance or calibration activities performed on it. Additionally, sensors are typically operated by different kinds of software, tailored for gathering and processing acquired data, generating signals, and executing specific functions such as configuration, calibration, monitoring, and diagnostics. To represent this operational software, we employ the *crmdig:D14 Software* class that was chosen due to its comprehensive semantic features allowing for the modelling of all of the software components of the Reactive Digital Twin. While the *crmdig:D14* class already provides the necessary features to model the software components of any device, we deemed it important to explicitly represent the relationship between the sensor and its controlling software. For this reason, a specific *HP11 is operated by* property was introduced to indicate the close interconnection existing between the sensor and the software that controls it. This also enables the link between the software, the measurement operations performed by the sensor, and the digital signals generated from them.

Measurements and Signals

In a CIDOC CRM perspective, the measurement operations performed by sensors can be modelled as events. A sensor measurement event, in fact, involves the collection of data identifying various modifications of conditions on the object or in the environment under examination, within a certain spatiotemporal interval. In accordance with these features, we defined the *HC13 Sensor Measurement* class as a subclass of the *crmsci:S21 Measurement* to describe the measurement events performed by the sensors connected to digital twins. The *crmdig:L12 happened on device* property is used to specify the sensor (*HC9*) on which the measurement (*HC13*) took place. Measured events can instead be modelled by means of the *crm:E5 Event*, a class particularly well suited for describing generic events of various types. The measurement (*HC13*) and the measured (*crm:E5*) events are ontologically related through the *crmsci:O24 measured*. Instances of the *crm:E55 Type* class can be assigned to instances of *HC13* to detail, among the other things, the detected types of risk conditions related to the monitored cultural object, and subsequently trigger the generation of the corresponding signals. This assignment is usually carried out by means of the *crmdig:L17 measured thing of type* property.

Generated signals can be modelled as digital objects since they codify a measurement taken by a sensor to be transmitted, under certain conditions, to the system for further processing or analysis. Typically, a signal is a piece of software encoded in a formal language (e.g., XML, JavaScript, etc.) and generated in response to a specific event, such as a change in sensor reading, a threshold crossing, or a specific timer. It may contain various information, including sensor identifiers, timestamps, recorded values, measurement units, and details about condition assessment quality. In RHDTO, instances of signals are represented by means of the *HC12 Signal* class, a specialisation of the *crmdig:D9 Data Object* class. Signals (*H12*) generated in the presence of a potential risk detected by sensors can be linked to the measurement event that generated them through the *crmdig:L20 has created* property. Once generated, signals are transmitted to the digital twin and specifically to dedicated intelligent digital agents (deciders) running as part of their digital twin system. The transmission of signals to deciders is recorded via the *HP12 was transmitted to* property.

Deciders

The RHDTO provides a *HC10 Decider* class, specialising the scope of *crmpe:PE1 Service*, to describe in detail the deciders and their features. Deciders can receive and analyse input data from various sources, such as sensors, actuators, or other services, and query the digital twin knowledge base to acquire knowledge concerning the linked cultural objects and their potential risks. They further process all of this information using algorithms, rules, or models and generate output instructions, such as commands, feedback, or status updates, to be sent to other components of the digital twin, to actuators, or to other external devices. Moreover, deciders can also send alerts to human operators in various forms, such as email, SMS, push notifications, and visual or audible alerts, depending on the nature of the detected issue.

Ontologically, the actions performed by deciders after the decision-making process is complete can be modelled as events. Thus, we have designed a specific *HC14 Activation Event* class, a subclass of the *crm:E5 Event*, to represent them. The *crmsci:O13 triggered* property is particularly useful for linking activation events to the deciders by which they were triggered. Activation events can prompt specific actions by digital agents, such as adjusting a valve or activating a pump, and/or alert human operators, informing them of the necessary countermeasures to be taken in response to the detected potential risks. Both operations are modelled by means of the *HP14 alerted* property, pointing to instances of the *crm:E39 Actor*, and *HP13 activated*, linking activation events with actuators.

Actuators

Actuators are other fundamental components of digital twins. In RHDTO, they are described as devices that enact actions upon physical objects or processes based on the instructions received by the deciders operating within the digital twin system. They can be of mechanical, electrical, digital, hydraulic, or pneumatic types, and can execute a range of actions, including movement, adjustment, control, or regulation. Actuators may operate in distinct modes, including automatic, manual, or semi-automatic, and can be governed by various software systems, such as firmware, drivers, or applications. Moreover, they offer various degrees of precision, accuracy, and responsiveness, contingent upon their design, fabrication, and maintenance processes.

Actuators interact with the digital twin through multiple channels, including sensors, APIs, or communication protocols, enabling the reception of commands, feedback, or status updates from the system. Given their specialised nature, we have defined the *HC11 Actuator*, subclass of *crmdig:D8 Digital Device*, to describe these peculiar devices. As in the case of sensors, actuators may be operated by software (again encoded through the *crmdig:D14 Software* class) intended for interpreting the commands and feedback coming from the Reactive Digital Twin system and controlling the actuator's actions accordingly.

As already anticipated, the *crm:E39 Actor* class is used to represent people and/or institutions responsible for the safety and security of cultural entities and their environment. These are the people who (may) receive alerts from deciders in order to take appropriate actions in the case of risky events. The *HP14 alerted* property is used in this case to associate an instance of *HC14 Activation Event* with an instance of *crm:E39 Actor*, indicating the alerts sent to the specified individuals or groups. This property is of particular interest since it describes the modalities of interaction and collaboration between the digital system and the real world, making particularly evident, also on the ontological level, the importance of the human component for the effective prevention and management of dangerous situations.

Artificial Intelligence

The use of Artificial Intelligence (AI) provides a significant enhancement to the reactive components of Heritage Digital Twins by optimising the operational scope of the Decider. AI technologies improve the efficiency of this component, particularly in scenarios demanding real-time responses, by refining its decisional logic to allow for faster and more effective actions. By means of its capacity to process vast and heterogeneous data—including historical records, real-time sensor inputs, and scientific information—AI enables the formulation of more comprehensive and accurate preservation strategies based on the identification of complex patterns and evolving information.

Moreover, AI facilitates a transition from a reactive to a proactive preservation model. Its predictive analytics capabilities allow the system to anticipate future trends and potential risks, thereby enabling preventative action before issues arise. This process is supported by the capture and historicisation of the Decider's actions and their context, generating records of decision chains within the knowledge graph that can be utilised to improve subsequent decision-making processes. To optimise these features, the AI can undergo targeted training by means of expert-generated documents, such as conservation reports and restoration protocols. Its performance can be further tested and refined through simulated risk scenarios, establishing an iterative loop wherein simulation outcomes are reintegrated into the training process to ensure continuous improvement.

Therefore, the RHDTO provides various entities to model the various components involved and capture their complex interactions. In particular, we introduced a new class, *HC15 AI Component*, representing the AI component within the digital twin system and describing its role in automating and enhancing various processes performed, such as data analysis, decision-making, and predictive modelling. These processes are represented by the new HC16 Simulation and Prediction class so that they can be recorded in the digital twin's knowledge base to be examined and reused by AI in future scenarios.

A schematic overview of the reactive components of the RHDTO model and their semantic relationships is illustrated in Figure 2.

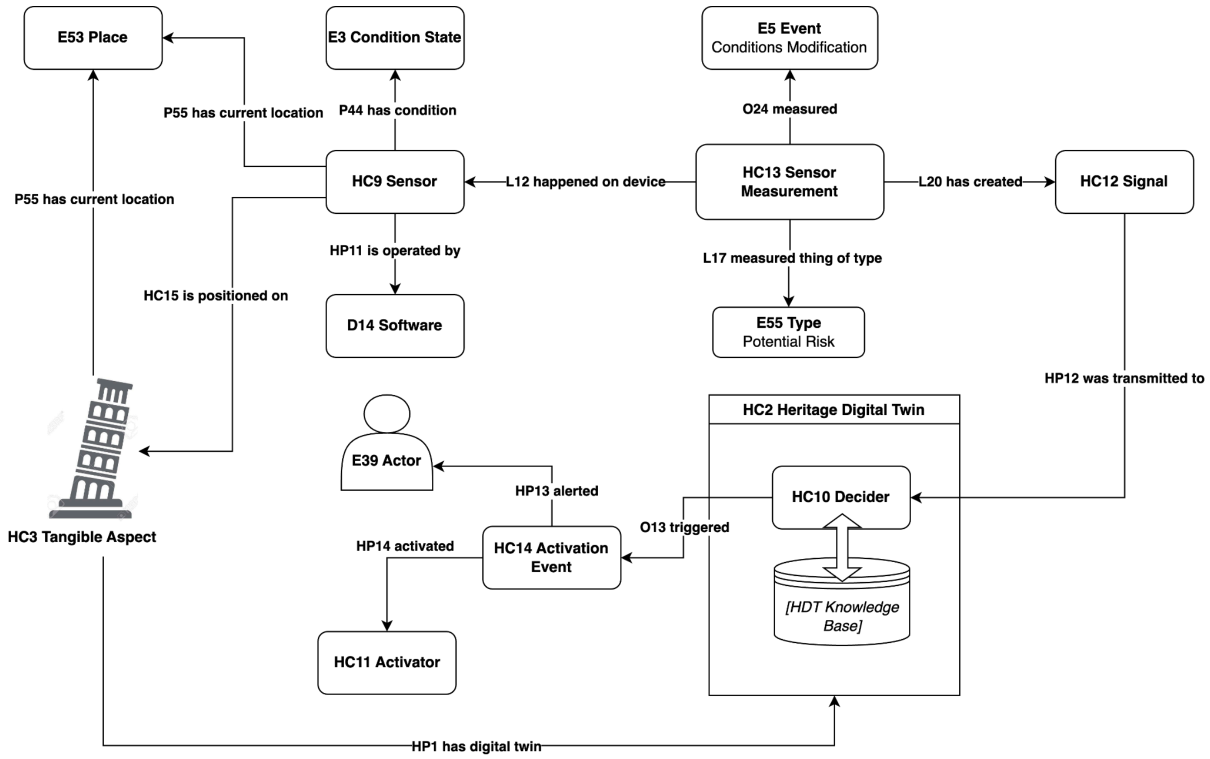

Figure 2: Overview of the reactive components of the RHDTO model.

RHDT Ontology Usage Examples

Defining Digital Twins of Heritage Entities

The following example illustrates how RHDTO and the entities of the CIDOC CRM ecosystem, on which the ontology is built, can be used to model various aspects of cultural objects. For this example, we focus on the Baptistery of Florence (Italy) and its famous bronze doors, which hold significant artistic value[3].

The schema shown in Figure 3 demonstrates how the material and intangible aspects of the Baptistery have been represented by combining the classes and properties of RHDTO with those of CIDOC CRM. The Baptistery can be described using the *HC3 Tangible Entity*. It comprises multiple elements, among which the eastern door, known as the "Gates of Paradise" by Lorenzo Ghiberti, is particularly noteworthy. This door can also be represented using the *HC3* class. The association of the door with the Baptistery is expressed through the CRM property *crm:P46 is composed of*, which directly links physical objects to their components. The respective locations of the two artifacts (*HC3*) are conveyed using the *crm:P55 has current location* and the *crm:E53 Place* class.

The Baptistery and its parts are referenced in numerous literary works, modelled using the *nont:Narrative* class. Among these are Michelangelo's remark about the door and Dante's verses regarding the Baptistery. The relationship between the instances of *HC3* and the works that refer to them can be expressed through the *HP2 has story* property. The *crm:P70 is documented in* property directly connects the Baptistery to this documentation.

[3] For the Baptistery and its history, see: https://en.wikipedia.org/wiki/Florence_Baptistery.

Furthermore, the Baptistery and its components are depicted in numerous photographs (*HC7 Digital Visual Object*) and digital reproductions, as well as being replicated in various three-dimensional models (*HC8 3D Model*). These elements can be linked to the cultural object they represent through the *HP9 has visual representation* property. Finally, the connection between the various *HC3* elements and their replicas in the digital realm (*HC2 Heritage Digital Twin*) is expressed via the *HP1 has digital twin* property. The same relationship that links the monument and its components in the physical world can also be replicated for their digital representations, such that the digital twin of the Baptistery (*HC2*) is connected to the digital twin of the eastern door (*HC2*) via the *HP3 is digital twin component of* property.

The modeling of the Baptistery, its components and its digital twins by means of the RHDTO classes and properties is exemplified in Figure 3.

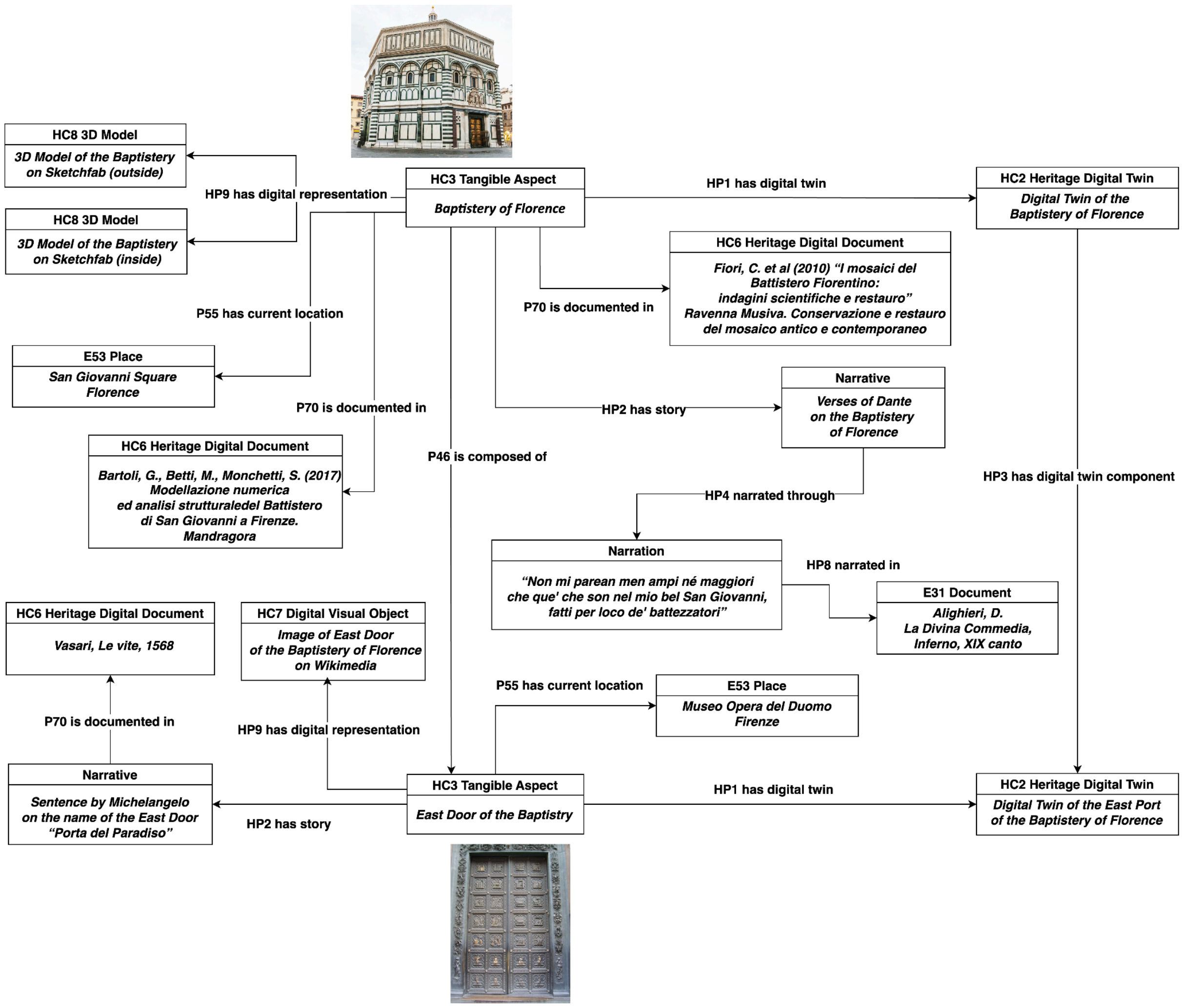

Figure 3: Semantic modelling of the the Baptistery of Florence using the RHDTO model.

Modelling Reactive Components of Heritage Digital Twins

The following example is intended to exemplify how a digital twin system using sensors, signals, deciders and actuators can be modelled by means of RHDTO. For this example we consider various monitoring operations carried on the pulpit in the church of Sant’Andrea in Pistoia (Italy), a medieval masterwork by the Italian sculptor Giovanni Pisano[4].

The physical system includes sophisticated sensors and takes into account previous work by a worldclass restoration centre based in Florence, the Opificio delle Pietre Dure (OPD). The array of sensors installed for the purpose of gathering environmental and dynamic data encompassed various types, among which were humidity sensors situated on the wall in the side nave adjacent to the pulpit, and uniaxial accelerometers positioned atop the pulpit and on the ground near its base. This specific configuration facilitated meticulous monitoring of both the environmental area surrounding the pulpit and any dynamic oscillations occurring on its surface.

To showcase the functionality of the RHDTO model in semantically representing this scenario, we specifically focus on these two types of sensors, illustrating how they can be semantically described using our classes and properties and integrated into the overall description of the installed monitoring system.

The Cultural Object

The semantic modelling starts by noting that Giovanni Pisano’s pulpit is a monument and thus a physical cultural object that can be represented by instantiating the *HC3 Tangible Entity* class. The church of Sant’Andrea in Pistoia (Italy) can be represented by an instance of the *crm:E53 Place*, while the fact that the pulpit is housed in this church can be rendered through the *crm:P55 has current location* property. Specific identifiers for both of these heritage entities can be defined and/or derived using for example the global identifiers provided by Wikidata, such as the https://www.wikidata.org/wiki/Q3925522 URI identifying the pulpit, or the https://www.wikidata.org/wiki/Q1148335 URI identifying Sant’Andrea’s church in the Wikidata system. The *HC2 Digital Twin* class can be instantiated to represent the digital twin of the pulpit in the semantic space of our model.

Sensors and Measurements

Instances of the *HC9 Sensor* class could be employed to represent the diverse types of sensors used to monitor the monument. We focus our example on two instances of this class used to represent the temperature and humidity sensor installed on the walls of the church and the uniaxial accelerator sensor positioned on top of the pulpit.

Regarding their specific position, the distinct placements of these two sensors are rendered either through the *crm:P55 has current location* property, used to indicate the positioning of the temperature and humidity sensor on the wall of the church, and the property *HC15 is positioned on*, used to specify the placement of the uniaxial accelerometer sensor directly on the surface of the monument. The *HP11 is operated by* property is utilised to establish the connection between the sensors and the corresponding instances of the *crmdig:D14 Software* class, employed to represent the software operating them.

An associated instance of the *HC13 Sensor Measurement* class is defined to specify, through the *crmsci:O24 measured* property, the type of event monitored by each sensor, and specifically, the

[4] For the Pulpit, see: https://en.wikipedia.org/wiki/Pulpit_of_Sant%27_Andrea,_Pistoia_(Giovanni_Pisano). The results of this monitoring activity are reported in: Marafini, F.; Betti, M.; Bartoli, Z.G.; Casarin, F.; Marchesini, F.; Barontini, A.; Mendes, N. Static and Dynamic Monitoring of Giovanni Pisano’s Pulpit in Pistoia (Italy). In SAHC 2023, RILEM Bookseries 47; Endo, Y., Hanazato, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2024; pp. 197–210. https://doi.org/10.1007/978-3-031-39603-8_17.

seismic movements detected through variations in acceleration by the uniaxial accelerometer, and changes in the temperature and humidity parameters of the church recorded by the temperature and humidity sensor. Both of these events are modelled by means of the *crm:E5 Event* class. The signals resulting from these measurements are represented by using the *HC12 Signal* class and linked to the event that generates them via the *crmdig:L20 has created* property.

Signals Transmissions

The signal transmission to the digital twin of the pulpit (*HC2*) is encoded through the *HP12 was transmitted to* property and the integrated monitoring system that receives them by instances of the *HC10 Decider* class. This is the system designed to acquire the transmitted values, analyse the various physical and environmental conditions of the monument, extend the information coming from other sensors, and enrich and interact with the digital twin's knowledge base.

Deciders and Actuators

The sensor system of Giovanni Pisano's pulpit does not include actuators, but just for the sake of exemplifying how the system would be described when including an actuator, we have added a hypothetic second part, not present in the actual system. In this supposed system, a decider (*HC10*) evaluates the variations in some measures from standard values and if they exceed a threshold, it sends an email to the *Opificio delle Pietre Dure* operators to intervene. This process can be semantically modelled by means of the *crmsci:O13 triggered* property and *HC14 Activation Event* representing the action of email transmission by the system to the OPD competent office (*crm:E39 Actor*). Figure 4 illustrates the semantics of this example to show the application of the RHDTO to a typical monitoring scenario for a heritage asset.

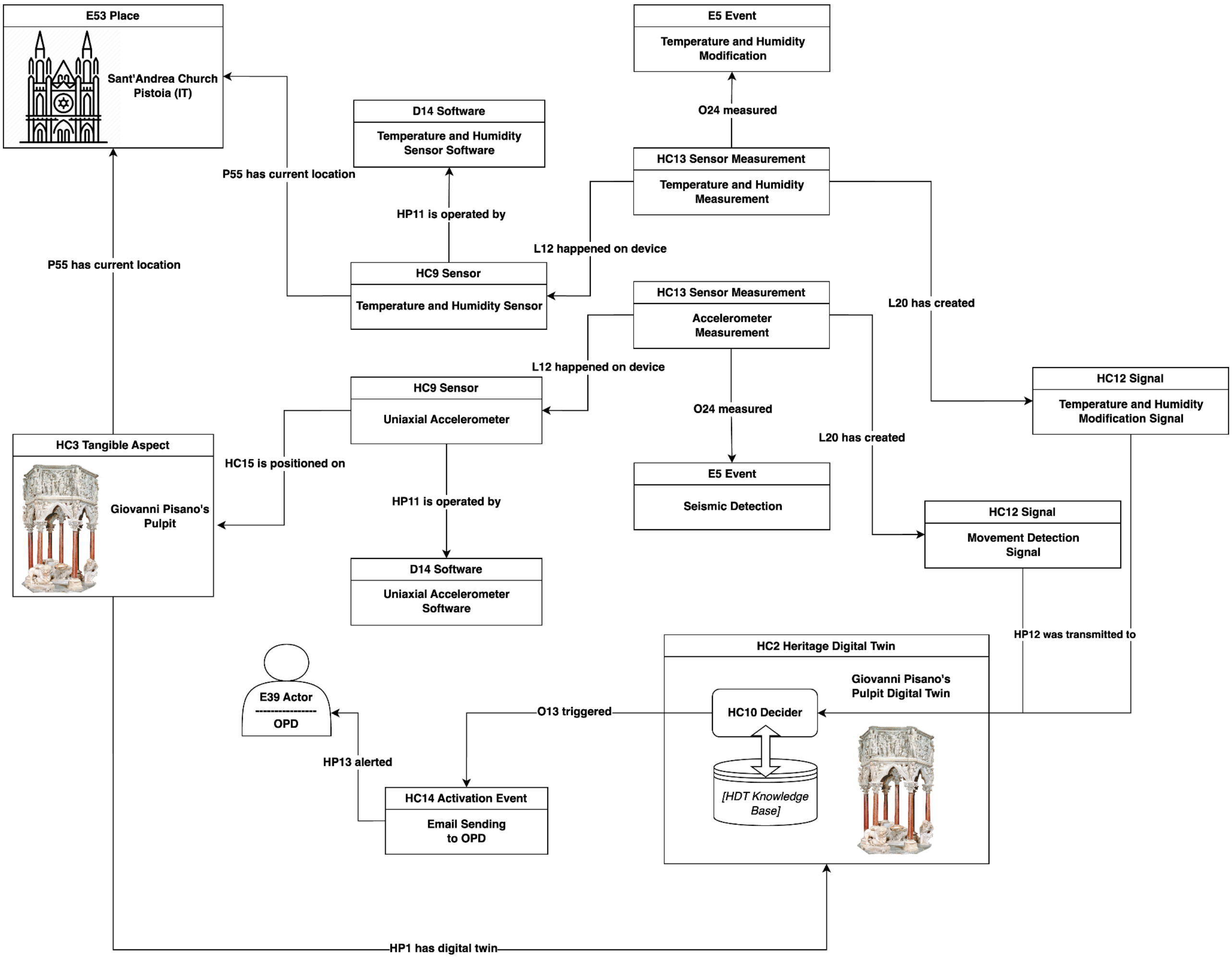

Figure 4: A semantic representation of the Giovanni Pisano’s pulpit monitoring system using RHDTO.

RHDTO Classes Declarations

The classes are comprehensively declared in this section using the following format:

- Class names are presented as headings in bold face, preceded by the class’s unique identifier.
- The line “Subclass of:” declares the superclass of the class from which it inherits properties.
- The line “Scope note:” contains the textual definition of the concept the class represents.
- The line “Examples:” contains a bulleted list of examples of instances of this class. If no examples are available for the described class, this line is omitted.
- The line “Properties:” declares the list of the class’s properties. Each property is represented by its unique identifier, its forward name, and the range class that it links to, separated by colons. If no properties have been defined for this class, this line is omitted.

HC1 Heritage Entity

Subclass of: crm:E1 CRM Entity

Scope Note: This class comprises tangible and intangible entities of the real-world regarded as valuable because of their contribution to society, knowledge and/or culture. Instances of HC1 Heritage Entity may refer to real assets of any nature: physical, both movable and immovable, immaterial, or born digital. They can also refer to cultural events, traditions and practices, typical of the intangible heritage, and can be used to describe their features and their extent in space and time. In the case of events, we can create instances of event types. An instance of HC1 can be considered as the entry point for inferring the content of its corresponding HC2 instance, even if by using crm:P148 has component property it can also be used for denoting HC2's components.

Examples: the Knossos Palace, part of the Knossos WH archaeological site
the Pafos Gate in Nicosia
the "Palio di Siena"
the Florence Historical Centre, a WH Site
the Stonehenge Complex, a WH site
the Bauhaus style

Properties: HP1 has digital twin (is digital twin of): HC2 Heritage Digital Twin
HP2 has story (is story about): nont:narrative
crm:P70 is documented in (documents): HC6 Digital Heritage Document
HP9 has visual representation (is visual representation of): HC7 Digital Visual Object
crmdig:L1 was digitized by (digitized) D2 Digitization Process crmdig:L11 had output (was output of): HC8 3D Model13

HC2 Heritage Digital Twin

Subclass of: crm:E89 Propositional Object

Scope Note: The class consists of the information available in a given system and pertaining to an HC1 Heritage Entity. Every instance of HC1 Heritage Entity is linked to one instance of HC2 Heritage Digital Twin, which provides an archive of the documented history of the corresponding HC1 Heritage Entity. It includes digital representations of that Heritage Entity (e.g. 3D models, images, videos), textual descriptions (e.g. digital documents, narrations or stories), information of the effects on the related HC1 Heritage Entity of events that influenced or/and are related in any way to its state of (e.g. earthquakes, floods etc.) and of activities (e.g. restorations, conservations etc.) carried out on it.

Examples: The HDT of Pisa Leaning Tower
The HDT of the Neptune Fountain in Bologna
The HDT of Knossos Palace
The HDT of the Pafos Gate in Nicosia
The HDT of the "Palio di Siena"
The HDT of the Florence Historical Centre

Properties: HP3 is digital twin component of (has digital twin component): HC2 Heritage Digital Twin

HC3 Tangible Entity

Subclass of: HC1 Heritage Entity
crm:E18 Physical Thing

Scope Note: This class comprises tangible, material entities of the real-world, both movable (e.g. archaeological, artistic and cultural objects) and immovable (e.g., built heritage like monuments, buildings, cities and other complexes), regarded as valuable because of their contribution to society, knowledge and/or culture. The “tangible” term in the name of this class does not exclude that its instances also possess an intangible aspect, which is specified through the HP5 has intangible aspect property.

Examples: The Neptune Fountain in Bologna (Italy)
The Pisa Leaning Tower, a UNESCO World Heritage (WH) Site
The Nike of Samothrace of the Louvre Museum in Paris (France)

Properties: HP5 has intangible aspect (is intangible aspect of): HC4 Intangible Aspect
HP7 is manifestation of (is manifested by): HC4 Intangible Aspect

HC4 Intangible Aspect

Subclass of: HC1 Heritage Entity
crm:E89 Propositional Object

Scope Note: This class comprises cultural events, traditions and practices having particular social, historical and cultural significance, including practices and expressions, memories and oral traditions about events, things, people.

Examples: The Mediterranean diet
Falconry
The Rebetiko music tradition
The “Palio di Siena”

Properties: HP6 has manifestation event (event is manifestation of): crm:E5 Event

HC5 Digital Representation

Subclass of: crmdig:D1 Digital Object

Scope Note: This class comprises the digital virtual representations of an HC1 Heritage Entity such as e-texts, images, audio or video items, 3D models, etc., that are documented as single units.

Examples: The digital version of Vasari’s “Vite”
The video https://www.youtube.com/watch?v=P1Uv4Zf5xKk

The Pafos Gate laser scanning 3D model

HC6 Digital Heritage Document

Subclass of: HC5 Digital Representation

Scope Note: This class comprises pieces or collections of digital, non-visual documents, either born-digital or digitised from physical, real-world ones, typically containing textual or numerical information regarding an HC1 Heritage Entity and intended to become part of the related HC2 Heritage Digital Twin. Documentation of this kind may include scientific data, research results and interpretation, as well as historical and cultural information, including textual descriptions related to the nature, conditions, positioning and to the whole set of events in which the cultural entity has been involved and the actors who have participated in them.

HC7 Digital Visual Object

Subclass of: HC5 Digital Representation

Scope Note: This class comprises digital visual objects, such as photos and videos, but also special imagery such as X-ray images, spectra of chemical and physical analyses, and so on, intended to become part of the HC2 Heritage Digital Twin of an HC1 Heritage Entity. Digital documentation of this kind can be born digital or digitised from physical objects (such as paper photographs, drawings and so on). Particularly relevant digital visual objects are also Virtual Reality (VR) and Augmented Reality (AR) models, other types of visual digital artefacts pertaining to a HC1 Heritage Entity. Both VR and AR models rely on 3D models of the related heritage entity, but may add or remove parts of it, or require further digital input as in AR, so they should be catalogued separately from 3D models.

Examples: The Europeana digital version of the paper picture of the Pisa Leaning Tower taken by Paolo Monti in 1960: https://www.europeana.eu/it/item/9200369/webclient_DeliveryManager_pid_6363979_custom_att_2_simple_viewer.

HC8 3D Model

Subclass of: HC5 Digital Representation

Scope Note: This class is used for rendering in detail the 3D model of HC1 Heritage Entity and intended as a particular crmdig:D1 Digital Object having its definite identity and resulting from operations such as digitization, acquisition, processing and other actions typical of the three-dimensional modelling world (e.g., 3D scanning, wireframe modelling and so on). The particular features of a 3D model (e.g., its type, format, resolution, size, etc.) and its relationships with the series of activities carried out for its creation and manipulation are modelled through the properties inherited from its superclass HC5, which in turn inherits from crmdig:D1 Digital Object, and through the other classes and properties of CRMdig.

Examples: The 3D model of the Neptune Fountain produced by ISTI-CNR (Pisa, Italy) as part of the documentation used for the restoration of the Neptune Fountain in Bologna (Italy): https://www.cnr.it/en/focus/074-43/3d-supported-restoration-the-neptune-fountain-in-bologna.

HC9 Sensor

Subclass of: crmdig:D8 Digital Device

Scope Note: This class comprises specialised devices utilised for monitoring and evaluating the conditions of artifacts, structures, or environments of historical significance. These devices are designed to detect changes in parameters such as temperature, humidity, vibration, or light exposure which may impact the conservation of cultural assets. Operated by dedicated software, sensors can exist in various states, including active, standby, or alert. For example, a temperature sensor may indicate fluctuations that could endanger delicate artifacts like manuscripts or artworks. When certain predefined thresholds are surpassed, the sensor enters an alert state, signalling potential risks and prompting appropriate intervention measures.

Examples: The temperature and humidity sensor installed on the walls of the church of Sant'Andrea in Pistoia (Italy).
The uniaxial accelerator sensor positioned on top of the Pulpit of Giovanni Pisano in the Church of Sant'Andrea in Pistoia (Italy).

Properties: HP11 was operated by: crmdg:D14 Software
HP15 was positioned on: HC3 Tangible Entity

HC10 Decider

Subclass of: crmpe:PE1 Service

Scope Note: This class comprises software components responsible for receiving signals from sensors and autonomously making decisions aimed at safeguarding cultural objects. Acting as an intelligent service within the conservation systems of the digital twin, deciders process incoming data from sensors and information stored in the digital twin knowledge base to detect factors such as environmental conditions, artifact vulnerability, and conservation protocols. Based on this analysis, it executes predefined algorithms or decision-making rules to determine appropriate actions for preserving cultural heritage. These actions could include adjusting environmental controls, activating protective measures, or triggering alerts to conservators or relevant personnel when necessary.

Examples: The component of Giovanni Pisano's Pulpit digital twin designed to acquire the transmitted values, and analyse the various physical and environmental conditions of the monument.

HC11 Actuator

Subclass of: crmdig:D8 Digital Device

Scope Note: This class comprises digital devices responsible for executing actions determined by the decider of the digital twin system to safeguard cultural objects. Serving as a crucial link between decision-making and practical implementation, the actuator translates directives from the decider into tangible interventions aimed at mitigating risks or optimising conservation conditions. Interventions may encompass a variety of mechanisms, including the activation of mechanical, electronic, pneumatic, or hydraulic systems, among others. Actuators ensure the timely and effective execution of proactive conservation strategies, contributing to the long-term preservation of cultural heritage assets.

Examples: The component of Giovanni Pisano's Pulpit digital twin responsible for executing actions determined by the decider to safeguard the monument.

HC12 Signal

Subclass of: crmdig:D9 Data Object

Scope Note: This class is used to model particular data objects generated by sensors and to document specific detected conditions. Signals are typically transmitted to the digital twin, where they are processed and analysed by the system's algorithms to generate insights into the condition and conservation needs of cultural heritage. Signals may be encoded in a specific data formatting language, facilitating efficient transmission, storage, and analysis. Utilising standardised formats ensures interoperability and compatibility among different sensor systems and conservation platforms, including the digital twin knowledge base, enabling the seamless integration of data from diverse sources for comprehensive conservation management. The incorporation and analysis of encoded signals enables the digital twin to support informed decision-making and proactive preservation strategies for cultural heritage assets.

Examples: The data generated by the uniaxial accelerator sensor installed on the Pulpit of Giovanni Pisano in the Church of Sant'Andrea in Pistoia (Italy).

Properties: HP12 was transmitted to: HC9 Decider

HC13 Sensor Measurement

Subclass of: crmsci:S21 Measurement

Scope Note: This class comprises specific measurement events in which a sensor detects and quantifies a specific parameter or condition relevant to the monitoring and conservation of cultural assets. Events of this kind occur when a sensor registers changes in parameters such as temperature, humidity, light exposure, or vibration, capturing information that reflects the environmental conditions surrounding cultural objects or structures. Sensor measurement is thus an essential feature for continuously assessing the time and circumstances in which conditions of risk may affect cultural heritage, providing valuable insights into factors that may impact the preservation of artifacts or sites over time.

Examples: The measurement event that detected the seismic movements through variations in acceleration by the uniaxial accelerometer installed on the Pulpit of Giovanni Pisano in the Church of Sant'Andrea in Pistoia (Italy).

HC14 Activation Event

Subclass of: crm:E5 Event

Scope Note: This class serves to model actions performed by an actuator to initiate specific interventions or alerts aimed at safeguarding cultural assets. Activation events occur when an actuator executes directives received from the digital twin's decider, triggering actions such as activating climate control systems, deploying protective enclosures, or alerting personnel through various communication channels, including email notifications, SMS, and other similar ones.

Examples: The action of email transmission operated by the digital twin system of Giovanni Pisano's Pulpit to the *Opificio delle Pietre Dure* office.

Properties: HP13 activated: HC11 Actuator
HP14 alerted: crm:E39 Actor

HC15 AI Component

Subclass of: crmdig:D14 Software

Scope Note: This class is intended to model artificial intelligence systems integrated into the Heritage Digital Twin. AI components provide advanced capabilities for extracting and semantically encoding information from heritage documentation, continuously updating and enriching the digital twin's knowledge base. Additionally, instances of this class perform tasks such as data analysis, decision-making, and pattern recognition driven by algorithms or machine learning models, enhancing the analytical and predictive capabilities of digital twins to provide deeper insights into cultural entities and their historical and cultural context. Unlike conventional soft-ware, instances of HC15 simulate intelligent behaviour, learning from data and adapting to new conditions while making informed decisions. AI components are continuously trained using data stored in the knowledge graph, real-time data coming from sensors, and scientific documentation and protocols produced by experts, thus refining their responses through iterative feedback to prioritise key preservation factors. They also leverage physics-based models to infer conditions that cannot be directly observed, such as material degradation of cultural objects.

Properties: HP18 uses algorithm: crmdig:D14 Software
HP19 was trained using: crm:E31 Document

HC16 Simulation or Prediction

Subclass of: crm:E5 Event

Scope Note: This class is used to represent events of analysis, simulation, and prediction performed by the AI Component within the digital twin system, providing a structured way to document the AI's analytical activities. Simulations and predictions are critical components of the digital twin system, as they allow for the anticipation of future trends, the identification of potential issues, and the optimisation of decision-making processes. By performing simulations, the AI can test various scenarios and evaluate their impacts without the need for real-world experimentation. This is particularly useful in scenarios where real-time decisions are critical, such as emergency response or dynamic system optimisation. Predictions, on the other hand, enable the AI to forecast future states or events based on historical data and current conditions, providing valuable insights for proactive maintenance and conservation efforts.

RHDTO Properties Declarations

- The properties are comprehensively declared in this section using the following format.
- Property names are presented as headings in bold face, preceded by unique property identifiers.
- The line “Domain:” declares the class for which the property is defined.
- The line “Range:” declares the class to which the property points, or that provides the values for the property.
- The line “Subproperty of:” is a cross-reference to any superproperties the property may have.
  The line “Superproperty of:” is a cross-reference to any subproperties the property may have.
- The line “Scope note:” contains the textual definition of the concept the property represents.

HP1 has digital twin (is digital twin of)

Domain: HC1 Heritage Entity
Range: HC2 Heritage Digital Twin

Scope Note: This property links an instance of HC1 Heritage Entity with an instance of its related HC2 Heritage Digital Twin in a given system.

Examples: The Pafos Gate in Nicosia, Cyprus (HC1) has digital twin (HP1) the Pafos Gate digital twin (HC2) created by Cyprus Institute.

HP2 has story (is story about)

Domain: HC1 Heritage Entity
Range: nont:Narrative

Scope Note: This property links an instance of HC1 Heritage Entity with an instance of a nont:Narrative that refers to it.

Examples: Falconry has story (HP2) the history of Falconry over the centuries.

HP3 is digital twin component of (has digital twin component)

Domain: HC2 Heritage Digital Twin
Range: HC2 Heritage Digital Twin

Scope Note: This property associates an instance of HC2 Heritage Digital Twin with another HC2 of which is component. The term 'component' here is not limited to physical or geographical relationships (see examples), but encompasses any kind of main-associated relationship.

Examples: The HC2 Digital Twin of Pafos Gate in Nicosia (Cyprus) HP3 is a digital twin component of the HC2 Digital Twin of Nicosias' City Walls.
The HC2 Digital Twin of the "Cento Camini" Medici Villa in Artimino (Florence) HP3 is a digital twin component of the HC2 Digital Twin of the UNESCO WHS Medici Villas in Tuscany.
The HC2 Digital Twin of Vichy is a HP3 digital twin component of the HC2 Digital Twin of the UNESCO WHS The Great Spa Towns of Europe.
The HC2 Digital Twin of the "Basilica of San Salvatore in Spoleto, Italy" is a HP3 digital twin component of the HC2 Digital Twin of "Spoleto", which is a HP3 digital twin component of the UNESCO WHS "Longobards in Italy. Places of Power".

HP4 narrates (is narrated through)

Domain: nont:Narration
Range: nont:Narrative

Scope Note: This property links an instance of nont:Narration with an instance of a nont:Narrative which has this narration. It is similar to the nont:hasNarration property, but is not a subproperty of crm:P148 has component.

Examples: The “De Arte Venandi Cum Avibus” treatise by the Holy Roman Emperor Frederick II narrates (HP4) the history of Falconry.

HP5 has intangible aspect (is intangible aspect of)

Domain: HC3 Tangible Entity
Range: HC4 Intangible Aspect

Scope Note: This property associates an instance of HC3 Tangible Entity with its intangible aspects (HC4), i.e. the cultural, social and historical value it incorporates.

Examples: The “Theotokos of Vladimir” (HC3) icon HP5 has intangible aspect the secular veneration that is addressed to it (HC4).
The UNESCO WHS site “Routes of Santiago de Compostela” (HC3) has intangible aspect (HP5) pilgrimage to Santiago (HC4).

HP6 has manifestation event (event is manifestation of)

Domain: HC4 Intangible Aspect
Range: crm:E5 Event
SubPropertyOf: crm:P129 is about (is subject of)

Scope Note: This property associates an instance of HC4 Intangible Aspect with the instances of the crm:E5 Event (or of the unique and specific crm:E5 Event) through which the intangible entity manifests itself in the physical world.

Examples: The Palio di Siena (HC4) has manifestation event (HP6) the historical horse race that was held in Siena on 17/8/2022 (crm:E5)

HP7 is manifestation of (is manifested by)

Domain: HC3 Tangible Entity
Range: HC4 Intangible Aspect

Scope Note: This property associates instances of HC3 Tangible Entity with the HC4 Intangible Aspect of which they are the manifestation in the physical world.

Examples: The set of devotional graffiti engraved on the walls of the Church of the Holy Sepulchre in Jerusalem (HC3) is the manifestation of (HP7) the pilgrimage of which the church is the final destination (HC4).

HP8 is narrated in document (document used for narration)

Domain: nont:Narration
Range: crm:E31 Document

Scope Note: This property associates an instance of nont:Narration with instances of E31 Document used to implement it.

Examples: The "De Arte Venandi Cum Avibus" treatise by the Holy Roman Emperor Frederick II (nont:Narration) is narrated in document (HP8) the "MS. Lat. 419" manuscript , now in the library of the University of Bologna E31.

HP9 has visual representation (is visual representation of)

Domain: HC1 Heritage Entity
Range: HC7 Digital Visual Object

Scope Note: This property associates an instance of HC1 Heritage Entity with instances of HC7 Digital Visual Object in which it is represented.

Examples: The Pisa Leaning Tower (HC1) has visually representation (HP9) the Europeana digital version of the paper picture of the Pisa Leaning Tower taken by Paolo Monti in 1960 (https://www.europeana.eu/it/item/9200369/webclient_DeliveryManager_pid_6363979_custom_att_2_simple_viewer) HC7.

HP10 tells about (is told by)

Domain: nont:Narrative
Range: crm:E5 Event

Scope Note: This property is intended to identify the specific events (crm:E5) to which a nont:Narrative relates.

Examples: The history of Falconry (nont:Narrative) tells about (HP10) the writing of "De Arte Venandi Cum Avibus" treatise by the Holy Roman Emperor Frederick II (crm:E5).

HP11 was made by (made)

Domain: HC3 Tangible Entity
Range: crm:E39 Actor

Scope Note: This property associates instances of HC3 Tangible Entities with instances of E39 Actor representing their author(s) or maker(s). This property is a shortcut of the CIDOC CRM fully developed path: E18 Physical Thing → P92 was brought into existence by → E63 Beginning of Existence → P11 had participant → E39 Actor.

Examples: "De Arte Venandi Cum Avibus" treatise HP11 was made by the Holy Roman Emperor Frederick II (crm:E39 Actor).

HP12 was made within (is making time-span of)

Domain: HC3 Tangible Entity
Range: crm:E52 Time-Span

Scope Note: This property associates instances of HC3 Tangible Entities with instances of E52 Actor during which they were brought into existence. This property is a shortcut of the CIDOC CRM fully developed path: E18 Physical Thing → P92 was brought into existence by → E63 Beginning of Existence → P4 has time-span → E52 Time-Span.

Examples: "De Arte Venandi Cum Avibus" treatise, HP11 was made within 1240 (crm:E52 Time-Span).

HP13 was operated by (operated)

Domain: HC9 Sensor
Range: crmdig:D14 Software

Scope Note: This property links an instance of HC9 Sensor to the instances of D14 Software that operate it. The software is usually a piece of code running on the sensor and responsible for controlling and managing it, for instance by configuring its settings, collecting and processing its data, and generating signals based on its measurements.

Examples: The uniaxial accelerator sensor positioned on top of the Pulpit of Giovanni Pisano in the Church of Sant'Andrea in Pistoia (Italy) was operated by (HP11) uniaxal accelerator software (crmdig:D14).

HP14 was transmitted to (received)

Domain: HC11 Signal
Range: HC9 Decider

Scope Note: This property associates the instances of HC11 Signal with the instances of HC9 Decider, indicating that a certain signal has been transmitted to the digital twin decider for processing. The property can be used to model the flow of data from sensors to the deciders and can be useful for tracking the status of signals and ensuring that they are properly processed by the decider. The property can also be used to model the relationship between signals and the specific decider services that process them, allowing for more fine-grained analysis and optimisation of the digital twin system.

Examples: The signal (HC11) generated by the uniaxial accelerator sensor installed on the Pulpit of Giovanni Pisano in the Church of Sant'Andrea in Pistoia (Italy) was transmitted to (HC12) the decider component (HC9) of Giovanni Pisano's Pulpit digital twin.

HP15 activated (was activated by)

Domain: HC14 Activation Event
Range: HC11 Actuator

Scope Note: This property associates the instances of HC14 Activation Event with the instances of HC11 Actuator, indicating the specific digital device activated by the digital twin system based on the decision made by the decider component regarding the actions to be taken according to the detected risk.

Examples: The activation event (HC14) generated by the decider of Giovanni Pisano's Pulpit digital twin, following the rise in temperature detected in the church of Sant'Andrea (Pistoia), activated the cooling system (HC11) of the church.

HP16 alerted (was alerted by)

Domain: HC14 Activation Event
Range: crm:E39 Actor

Scope Note: This property associates the instances of HC14 Activation Event with the instances of E39 Actor, indicating the action of alerting human personnel. The property can be used to model the communication between the digital twin and human operators, following the decision taken by the decider component, and to describe the modalities of collaboration and decision-making between the digital system and the real world.

Examples: The activation event (HC14) generated by the decider of Giovanni Pisano's Pulpit digital twin, following the seismic risk detected in the church of Sant'Andrea (Pistoia), alerted (HP14) the *Opificio delle Pietre Dure* by email.

HP17 was positioned on (hosted)

Domain: HC9 Sensor
Range: HC3 Tangible Entity

Scope Note: This property is used to model the spatial relationship between instances of HC9 Sensor and the physical object on which the sensors are located. The property is fundamental to document the specific case in which a sensor is physically placed on or attached to a cultural heritage physical object rather than being simply placed nearby or in the same environment as the monitored object.

Examples: A sensor (HC9) for the monitoring of temperature and humidity was positioned (HP15) on the walls of the church of Sant'Andrea in Pistoia (Italy).

HP18 uses algorithm (algorithm is used by)

Domain: HC15 AI Component
Range: crmdig:D14 Software

Scope Note: This property describes the specific algorithm or model employed by the AI Component within the digital twin system to process documentation efficiently, implementing its capability to draw meaningful conclusions from the analysed data. By recording this information, the property emphasises the methodological foundation of the AI component's functionality, underscoring its reliance on algorithmic approaches to achieve its objectives.

HP19 was trained using (was used for training)

Domain: HC15 AI Component
Range: crm:E31 Document

Scope Note: This property specifies the training documentation, protocols or datasets that were utilised to train the AI component, indicating that the AI has undergone a training process fundamental for enabling it to learn patterns, make predictions, and improve its performance in tasks related to cultural heritage documentation. This property is also essential for identifying the source and nature of the training data, which is critical for understanding the capabilities and limitations of the AI.

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