MONUMENT DAMAGE INFORMATION SYSTEM (MONDIS): AN ONTOLOGICAL APPROACH TO CULTURAL HERITAGE DOCUMENTATION

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ABSTRACT:

Deriving from the complex nature of cultural heritage conservation it is the need for enhancing a systematic but flexible organization of expert knowledge in the field. Such organization should address comprehensively the interrelations and complementariness among the different factors that come into play in the understanding of diagnostic and intervention problems. The purpose of MONDIS is to endorse this kind of organization. The approach consists in applying an ontological representation to the field of heritage conservation in order to establish an appropriate processing of data. The system allows replicating in a computer readable form the basic dependence among factors influencing the description, diagnosis and intervention of damages to immovable objects. More specifically MONDIS allows to input and search entries concerning object description, structural evolution, location characteristics and risk, component, material properties, surveys and measurements, damage typology, damage triggering events and possible interventions. The system supports searching features typical of standard databases, as it allows for the digitalization of a wide range of information including professional reports, books, articles and scientific papers. It also allows for computer aided retrieval of information tailored to user´s requirements. The foreseen outputs will include a web user interface and a mobile application for visual inspection purposes.

1. INTRODUCTION

Documentation represents an essential step in the context of heritage protection policies. Collection, management and sharing of information in fact contribute in a relevant manner to achieve a proper technical knowledge concerning worldwide cultural assets and to raise the necessary awareness regarding their socio-economical potential. Despite the abundance of data, the heterogeneity of documentation methodologies developed during time has produced a substantial incompatibility of contents resulting hence in integration problems. Interoperability between specialized systems and enhanced information access are revealed to be indeed crucial elements for endorsing research, administration and education activities. To overcome such problem innovative information techniques, based on semantic web technology, have increasingly been applied to data management of museums, local authorities and national trusts.
In this context, MONDIS provides an example of information system aimed at converging specialised knowledge in the field of cultural heritage protection under a unique but flexible representation of the domain, referred to as the ontology. The exploitation of ontologies for the purpose of knowledge mapping and sharing successfully conveys enhanced user accessibility, reliability of contents and possibility of integrating other information systems already existent in the domain. This paper presents the following structure: section 2.1 is devoted to the description of the monument damage ontology; section 2.2 presents the main functions of the MONDIS system; sections 3.1 and 3.2 outline the feasibility of using ontologies in the cultural heritage domain, presenting the advantages and limitations of such approach; section 3.3 explores the most relevant use cases providing details for the design of software applications.

2. MONDIS SYSTEM

2.1 Monument Damage Ontology

MONDIS focusses on the development of an ontological framework able to coordinate an automated reasoning behind the documentation of damages to built heritage, their diagnosis and possible interventions. The *Monument Damage Ontology* (Blaško et Al., 2012) aims at producing a conceptual model in which the factors relevant to cultural heritage domain and their interrelations are formalised. The approach employed in building the ontology consists of three different phases: individuation of relevant parameters necessary for the documentation of damages, taken from distinguished literature and international standards such as surveying forms and object classification guidelines; establishment of the relationships among factors, deriving from professional methodologies and workflows; testing the validity of the ontology section by section at public workshops and internal meetings.

Figure 1 shows the resulting graphical representation of the ontological model. The main concepts involved (referred to as

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classes) can be grouped, by colour coding, into thematic clusters.

The *component and construction description* section (in green) allows assigning the cultural heritage object with physical and functional characteristics: complex and normal objects can be described by defining respectively multiple or single constructions (defined as a distinguishable ´whole´ which contains components); structural and functional types provide further details concerning the resisting scheme of the construction and its functionality; component and its sub-components can be defined by determining a hierarchical organization of object´s parts (e.g. floor has sub component flooring which has subcomponent plank), finally material can be set for each component/subcomponent. Other parameters such as use and style complete the basic description of the construction.

The *events* cluster (in yellow) individuates those occurrences which can influence the conditions of the object (specified by a temporal reference). These include natural disasters, object changes and location characteristics changes. Natural disaster class is modelled as the activation of a hazard (e.g. earthquake hazard, flood hazard, landslide hazard etc.); object change class includes those sub classes which can produce a relevant impact on the state of the object, namely functional change (e.g. farm changes to a museum), structural change (e.g. component addition, removal or substitution), relevant damages and past (intrusive) interventions; location characteristics change class refers instead to changes in the geo-morphological, hydro-geological and environmental conditions of the site.

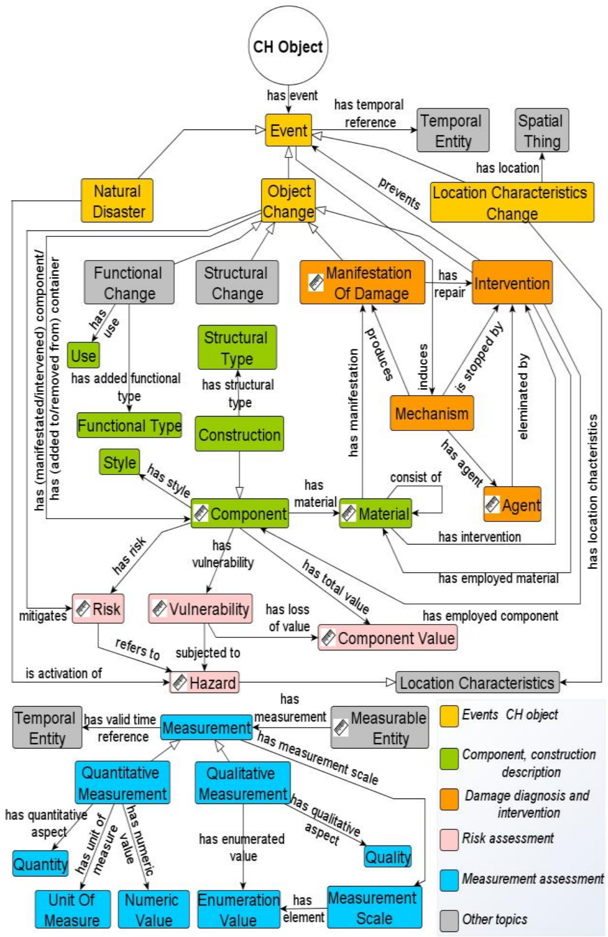

Figure 1. MONDIS Ontological Model

Events strongly relate to the *damage diagnosis and intervention* section of the model (in orange). The diagnostic phase is in fact represented by the interplay between events, mechanisms, agents and manifestation of damage. Events can induce damaging processes (referred to as mechanisms). Mechanisms (e.g. bending, capillary rise) in turn might result in the formation of a tangible and detectable damage (referred to as manifestation of damage) such as cracks, deflection, loss of material etc. Agents are defined as the carrying factors of a damaging mechanism (e.g. temperature or water). Intervention individuates those actions taken in order to prevent an event (e.g. fencing to prevent vandalism), to repair a manifestation of damage (e.g. filling to repair crack gaps), to stop a mechanism (e.g. strengthening to stop buckling) and to eliminate an agent (e.g. introduction of water proof membrane to eliminate water infiltration).

Risk assessment cluster (in pink) represents the interaction between hazard at a location, component vulnerability and component value. This section of the ontology provides useful insights on possible actions which could help mitigating the risk (such as preventive interventions) and, more importantly, on whether the situation is risky enough to require interventions or not.

In order to provide the possibility to assess the magnitude of some of the factors of the model, an independent *measurement assessment* cluster (in light blue) is proposed. This part of the ontology allows documenting qualitatively and/or quantitatively measurable entities (individuated in the model by ´📏´ icon): data concerning surveyed components (e.g. height or thickness of a wall), reported damages (e.g. width of a crack), measured agents (e.g. stresses in a pillar, moisture content in masonry) and risks (e.g. high risk of slender structures to earthquake).

The *other topics* cluster includes those classes necessary for the functioning of the model which are usually integrated from already existing ontologies (e.g. temporal entity, spatial thing).
It should be underlined that each class introduced in the model presents an internal structure called taxonomy. Taxonomies involve a hierarchical ordering of terms that enhances an appropriate categorisation of concepts based on the selection of a governing parameter (e.g. taxonomy of walls based on their structural characteristic). Taxonomies can be extracted directly from relevant literature such as for example damage catalogues (Snethlage, 2010).

2.2 Functions

The Monument Damage Ontology described in section 2.1 provides a platform on which the knowledge-based system is developed. MONDIS provides potential users with two basic actions to be performed, namely inputting and searching.

Inputting allows users to create an entry in the system and to insert data following a flexible and adaptable sequence of steps. This function enhances the digitalization of a wide range of information including professional reports, books, articles and scientific papers. Let´s consider for example documenting a damage produced by a seismic event on a masonry bell tower. The record would fit the model as follows:
OBJECT DESCRIPTION: construction type: tower; structural type: cantilever; functional type: bell tower; material: masonry;
EVENT: initial construction: 1300; earthquake: 2012 – *induces*→MECHANISM: In-plane mechanism (shear) – *produces*→ MANIFESTATION OF DAMAGE: Crack—*has*

measurement→QUANTITATIVE MEASUREMENT: (width) 4mm. The deductive processing of such information by the system allows the user to obtain for instance clues concerning possible interventions aimed at repairing the manifestation of damage (e.g. by injecting the crack) and at stopping the mechanism (e.g. by increasing shear resistance of the structure).

Inputting is thus supported by self-reasoning providing logical relationships between the information being inserted and that which already exists in the system. This characteristic considerably improves the ease to interact and cross-reference information and consequently the knowledge sharing.

Searching function permits exploring existing knowledge by computer-aided retrieval tailored to users´ query. The relationships among concepts formalized in the ontological model allow narrowing down searching to logically related information only maximizing the contextualization of the output. Let´s consider the case of searching for a generic masonry material. The system would provide a series of data related to the concept ´masonry´. Such data might include information concerning masonry properties (taken from MEASUREMENT ontology); masonry sub categories such as ´brick masonry´, ´stone masonry´ or ´mixed masonry´ (taken from the taxonomy of class ´MATERIAL´) and common damages presented by ´masonry´(by the relation MATERIAL—has manifestation→ ´MANIFESTATION OF DAMAGE´), just to mention a few. Whenever further parameters are set in the searching interface, for example the type of the component which is made of masonry (by using ´COMPONENT´ class), or its surrounding characteristics (setting ´LOCATION CHARACTERISTICS CHANGE´ class), the system would accordingly restrict the retrieval to more exact information. This feature takes into consideration the level of knowledge, which is the depth of information, of the users with respect to a specific field of expertise, therefore contributing consistently in adapting the system to context specific cases.

The simple input and search examples outlined above well explain the powerful tool that the ontology might represent in the context of a vast domain, such that of cultural heritage protection, which lacks adequate knowledge organization and non-expert user accessibility. Insights on the feasibility of exploiting the MONDIS system and model in the field of cultural heritage are presented in the following section of the paper.

3. APPLICATIONS TO CULTURAL HERITAGE DOCUMENTATION

Ontology provides a technique of how to represent data about a chosen application domain (Gruber, 2008). Although ontologies were successfully used in many domains of discourse, like biomedical applications (Bodenrider, 2008), e-government (Fogli, 2012), and others, damages to cultural heritage objects domain remains one of the prominent ones (Doerr, 2009). Due to the complexity, heterogeneity and distributed nature of the knowledge, digital content administrators use ontologies for semantic integration of different data in the field or data of variable level of granularity, as an alternative to fixed and hard-to-adjust relational databases.

Several semantic web ontologies were developed in the cultural heritage domain (Doerr, 2009), (Hyvoenen, 2012), including CIDOC CRM (Doerr, 2005), probably the most famous one in the field, aimed at semantic integration of cultural heritage data. Many ontological applications in the cultural heritage domain were focused on delivering digital content, related to cultural heritage artefacts, to the end-users (Doerr, 2009). An interesting example of current efforts in using semantic web technologies within the cultural heritage domain is Europeana (Valtysson, 2012), an EU-funded initiative which aims at collecting semantic metadata about various national cultural heritage sets and publishing their integrated version in a machine understandable way compliant with Linked Data principles (Heath at Al., 2011).

Most of the relevant work to date, however, presents some shortfalls in successfully integrating information concerning the wider historical context in which an object and the processes that govern its state are embedded. MIDAS, a British cultural heritage standard for monument inventories (MIDAS, 2012), and The Core Data Standard for Archaeological Sites and Monuments (Council of Europe, 1999), for example, translate their documentation standards to CIDOC CRM compatible ontology providing a framework for documenting monuments. Although such ontologies offer a solid methodological and technical background from which MONDIS stems out, their representation is nevertheless not rich enough for analysing the multi-faceted domain of historic buildings, especially as far as the relevance of damages and interventions in the perspective of heritage protection is concerned.

In comparison to previous works therefore MONDIS, with the Monument Damage Ontology, attempts to go beyond the conventional documentation of monuments, aiming at complementing existing ontologies with the possibility to describe monument damage, its causes and consequences.

Based on the proposed ontology, the MONDIS project endorses two software applications: (1) a mobile application providing computer support for on-site visual inspection of monument condition, (2) a web-based educational tool for visualizing dependencies between various qualities, including monument constructions, damages and materials. These applications are further described in section 3.3.

3.1 Feasibility

The structure of an ontology is defined in terms of classes and properties. Classes (e.g. Wall) represent collections of concrete things (e.g. front wall of Pisa tower) identified by some common characteristics (e.g. continuous structure dividing or enclosing an area), while properties represent relationships between things (e.g. Pisa tower "is located in" Italy).

In classical approaches, such as relational databases, data are stored in some predefined structure (database schema) while the meaning of the data is hard-coded in an application. On the contrary, ontologies bundle domain concepts with their precise meaning by means of both informal definitions and formal constraints, ensuring coherency of data. The independency of the meaning of concepts on both the reader and the context make ontologies an excellent tool for knowledge integration and sharing, providing hence a feasible alternative to conventional cultural heritage documentation systems.

MONDIS provides software applications which ' run' on the ontological model. The interaction between model and application is based on the fact that ontologies are declarative, allowing their processing by means of a generic *inference engine*. More specifically, in the MONDIS applications, the inference engine takes ontological knowledge, it deduces new knowledge and finally it provides the information back to the application user. The new inferred knowledge helps the application user to reveal new dependencies in the domain, or in other words to obtain coherent answers to the queries posed by the application itself. Although the feasibility of the ontological process within the context of cultural heritage documentation is proven on a global level, specific advantages and limitations are further discussed in the next paragraph in order to outline the technical borders when implementing the system.

3.2 Advantages and Limitations

Greater flexibility, easy integration and sharing, ability to manage incompleteness or impreciseness constitute the main advantages of employing ontologies for documentation purposes. Compared to databases the structure of an ontology proves to be quite dynamic: new classes and properties can be easily incorporated providing flexibility in evolving scenarios.
In addition, classes and properties within ontology are organized in hierarchies according to its generality (e.g. class Structure would be higher in hierarchy than class Wall). Such organization allows representing new knowledge with appropriate level of generality thus helping to cope with incompleteness or impreciseness of the data.

The ontologies already proved their potential in many domains, let's remind the Linked Data initiative mentioned at the beginning of this section, that contains hundreds of inter-linked ontological datasets from various domain. Their interlinking helps to pose inter-domain queries, while their ontological nature helps to infer new knowledge in the particular domain. Nevertheless, some drawbacks must be considered.
Firstly the development of an ontology is a very time-consuming process which requires both ontological engineers and domain experts to be involved. This physiological constraint can be a relevant one in case of short term projects and it might lead to either unrepresentative or ´stiff´ ontologies (i.e. too technical and not easy-to-grasp for users). The introduction of a common understanding as well as a common language in the building of the ontology is necessary. Furthermore although primary classifications of classes within the ontology, based on principles of ontology design, is very useful for integration purposes, it is often found to be rather artificial and not entirely user-friendly (Mizoguchi, 2003). It is in fact true in most of the cases that users prefer classification based on other simple criteria: for example instead of a classification of building materials based on essential properties of classes (e.g. strength properties), users might prefer a categorisation according to the use (e.g. hierarchy based on typical materials with respect to components: wood is used for joists and planks, glass for windows, RC for slabs). In such case the ontology needs to be enriched with secondary levels of classification in order to facilitate the interaction with primary one.

Secondly, there exists a problem of semantic interoperability due to incorrect use of basic patterns of ontology design (Poveda, 2010). This consists in a misinterpretation of the ontology engineering methodologies adopted and consequently in a misuse of the representation by the community of users. Interoperability among ontologies hence can be compromised by quality of existing ontologies. It most cases it is caused by low awareness of ontology engineering principles within the community itself (Mizoguchi, 2003).

Lastly, compared to classical approaches, development of ontologies as well as knowledge-based systems lacks easy enough tools to simplify the development process.

3.3 Use Cases

MONDIS aims at producing a number of different context-specific applications of the system for a wide range of users. Use cases are currently being formulated in order to explore the characteristics of the user-base and provide details for the design of these applications. Three use cases are presented. Their functioning is dependent on the characteristics of the ontological model presented in figure 1 and on the capacity of the inference engine to process and retrieve data, as explained in section 3.1.

3.3.1 Use case 1: Local or national authorities management systems.
This use case addresses reporters from cultural heritage authorities which require a supportive tool for in-situ identification of the object and assessment of its conditions following predefined standards adopted by their institution (e.g. damage level tables).

User: Administrator.
Objective of user: Assess conditions of monuments.
Data in possession of user: history of object, style, location, reference number (listed building), photos (history).

Goal:
- To help inputting of data directly on site.
- To improve knowledge about conditions of managed buildings.
- To enhance use of a standardised approach to determine the grade of danger of building.

Features:
- GPS localization.
- Attach pictures and reports.
- QR code reader (for labelled monuments only).

Description on how to interact:
Application is to be developed for portable devices. By GPS, it would possible to connect to existing database (obtaining data such as location, date of construction etc.). User should be able to fill in general data concerning the identity of the object and tick appropriate condition level, taken from valid standards enforced within the institution represented.

Advantages from using MONDIS:
- Digitalised information.
- Integration of existing databases (GIS).
- Extension of entry following model (in case a more accurate survey is required).

3.3.2 Use case 2: Learning support.
This use case considers the needs of non-professional users such as monument owners and students. A proper visualization of knowledge is required for allowing user friendly interaction with the system and understanding of information.

User: Students/ owners.
Objective of user: Searching of general knowledge (definitions, pictures), diagnosis and possible intervention for specific damage.
Data in possession of user: General data from case study: visual inspection including rough damage survey.

Goal:

- To provide appropriate visualization of stored knowledge.
- To help searching common causes of failures and appropriate intervention.

Features:
- Pictographic dictionary.
- Support wizard to guide user towards refined search.

Description on how to interact:
A smart and intuitive visualisation tool is necessary to provide simplified output of complex relationships among factors. A ´knowledge matrix´, whose parameters can be selected by the user, provides a simple searching interface useful also for non experienced users. Cells of the matrix contain knowledge searched for and may be further detailed by clicking.

Advantages from using MONDIS:
- Possibility to compare damage case to stored similar examples.
- Simple visualization of knowledge which, if required, can be extended to deeper level of information.
- Community-based support. The learning tool finds its validity on the reliability of data stored by experienced users.

3.3.3 Use case 3: Application to professional practice.
This use case describes specifics of the use of MONDIS system by professionals dealing with material issues. The domain of materials is in the scope of interest of a variety of professionals with different backgrounds including material scientists, practitioners, companies etc. Considering both the fast development of new conservation materials available as well as the increasing interest in documenting, understanding and rehabilitation of historical materials and technologies, MONDIS system offers a very flexible platform even for enhanced exchange of knowledge between theory and practice, practice and product development and material producers and academics.

User: Material scientist, production engineer, conservator
Objective of user: Assess data on materials according to type, physic-chemical characteristics, documented application, material analogies, typical deterioration etc.
Data in possession of user: Particular cases of material use, its damages/failures, reports of material analyses and research, generalized knowledge on material

Goal:
- To organize and access a wide spectrum of knowledge on both historical and modern conservation materials.
- To merge data on typology, chemical composition, physical properties, visual manifestation, mineralogical, geological and petrographical data, known application or use.
- To enable comparison according to recorded material documentation (macrophotographs, thin sections, SEM, XRD patterns etc.).
- To facilitate identification of particular material according its characteristics.
- To facilitate searching compatible or analogous materials.

Features:
- Referenced knowledge base on material characteristics and properties.
- Predefined interactive keys for identification of selected material types (e.g. stone, mortar, metals).
- Routines to sort and categorize particular material according to its properties.
- Location of possible historical sources of material (e.g. maps of quarries, sand resources, historical lime producers).

Description on how to interact:
Intuitive data accessing through multifactorial queries, standard classification trees of materials, interactive identification keys, GIS application

Advantages from using MONDIS:
- Possibility to search through huge amount of data on historical materials and conservation agents.
- Possibility to collect a wide spectrum of data on materials and to operate with at the very spot.
- Possibility to classify and sort materials by different criteria.
- Data on materials directly connected to particular monuments, constructions etc. and vice versa.
- Acceleration of feedbacks among theory, production and application of conservation material.

4. CONCLUSIONS

MONDIS is focussed on the development of an ontological framework (Monument Damage Ontology) able to facilitate computer reasoning behind cultural heritage objects´ damage documentation. Developed ontology model attempts to chart knowledge in this domain capturing causal relations between identified factors.
The result is a knowledge-based system aimed at enhancing data sharing and access, and integration of existing digital systems. It features two basic functions: inputting and searching. Versatility of the system is a major concern, therefore different use cases are being considered in order to develop software applications for every day practice: a version of the system for portable devices would help in situ assessment of building conditions according to some predefined assessment standards; an adequate visualization tool would enhance searching of knowledge for less experienced users, such as students and monument owners; finally another application can be considered for divulgation of expert knowledge among researchers and professionals. Concluding, the exploitation of ontologies for the purpose of damage mapping successfully conveys enhanced user accessibility, reliability of contents and possibility of integrating other information systems already existent in the domain.

5. REFERENCES

References from Journals:
Blaško, M., Cacciotti R., Křemen P., Kouba Z., 2012. Monument Damage Ontology. *Lecture Notes in Computer Science* (7616), pp. 221-230.

Bodenreider, O., 2008. Ontologies and Data Integration in Biomedicine: Success Stories and Challenging Issues. *Lecture Notes in Computer Science* (5109), pp. 1-4.

Mizoguchi, R., 2003. Tutorial on Ontological Engineering. *New Generation Computing* 21 (4), pp.365-384.

Valtysson, B., 2012. EUROPEANA: The digital construction of Europe's collective memory. *Information, Communication & Society,* 15(2), pp. 151-170.

References from Books:
Council of Europe, 1999. Core data standards for archaeological sites and monuments. *Documenting the cultural heritage,* R. Thornes, J. Bold (Eds.), Getty Trust Publication.

Doerr, M., 2009. Ontologies for Cultural Heritage. *Handbook on Ontologies,* Second Edition, S. Staab, R. Studer (Eds.). Springer, pp. 463-486.

Gruber, T., 2008. Ontology. *Encyclopedia of Database Systems,* Ling Liu and M. Tamer Özsu (Eds.), Springer-Verlag, pp. 1963-1965.

Heath, T., Bizer, C., 2011. *Linked Data: Evolving the Web into a Global Data Space (1st edition).* Synthesis Lectures on the Semantic Web: Theory and Technology. Morgan & Claypool, pp. 1-136.

Hyvoenen, E., 2012. *Publishing and Using Cultural Heritage Linked Data on the Semantic Web,* Synthesis Lectures on the Semantic Web: Theory and Technology, Morgan & Claypool, pp.1-119.

MIDAS Heritage, 2010. *The UK historic environment data standard,* English Heritage, UK.

Snethlage, R., 2010. *Illustrated glossary on stone deterioration patterns*. ICOMOS-ISCS, France.

References from Other Literature:
Doerr, M., 2005. The CIDOC CRM, an Ontological Approach to Schema Heterogeneity. In: *Proceedings of Semantic Interoperability and Integration*.

Fogli, D., 2012. Designing visual interactive systems in the e-government domain. In: *Proceedings of the International Working Conference on Advanced Visual Interfaces,* New York, USA, pp. 46-49.

Poveda, M., Suárez-Figueroa, M. C., Gómez-Pérez, A., 2010. Common pitfalls in ontology development. In: *Current Topics in Artificial Intelligence*. Springer Berlin Heidelberg, pp. 91-100.

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