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Semantically rich 3D documentation for the preservation of tangible heritage

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Abstract

Traditionally, 3D acquisition technologies have been used to record heritage artefacts and to support specific tasks such as conservation or provenance verification. These exercises are usually a one-off as the technology and resources required are cost intensive. However, there is a recent impetus on the creation of 3D collections to document heritage artefacts which are semantically enriched by using annotations. A requirement of these solutions is the ability to support several representations of a heritage artefact recorded through time. This paper will propose an infrastructure to systematically enrich 3D shapes in a collection by using propagated annotations. In addition, it will describe the mechanisms for annotating, propagating and structuring the annotations using the CIDOC-CRM ontology. The results of this research have the potential to support heritage organisations in making their semantically rich 3D content available to a wider audience of professionals.

Categories and Subject Descriptors (according to ACM CCS): E.2 [Data]: Data Storage and Representations—Linked representations H.3.1 [Information Systems]: Information Storage and Retrieval—Content Analysis and Indexing, Abstracting methods H.3.7 [Information Systems]: Information Storage and Retrieval—Digital Libraries[Collection] I.3.5 [Computing Methodologies]: Computer Graphics—Computational Geometry and Object Modeling[Object hierarchies]

1. Introduction

Progressively, heritage professionals are recognising the advantages of documenting in 3D their collections of artefacts. 3D collections are becoming an important element in the preservation and scholarly research of tangible Cultural Heritage (CH). The 3D digital representations of CH objects open the parallel access to more professionals, enabling the inspection of textures, the analysis of surface characteristics, the measurement of dimensions, and the examination of light behaviour, among many other activities. In this respect, the last years have seen significant effort towards addressing the different challenges of building 3D collections, not only for acquiring different types of artefacts, but also for managing and enriching this type of digital assets. Nevertheless, the isolated 3D digital representation of a CH object is not able to provide the full potential of such virtual surrogates. This potential can be reached, by means of enriching the 3D shape with semantics and related knowledge on the CH object. Thus, building an interconnected network of information and bringing together the 3D digital representation of the object with the information of the institution's document management system at a glance.

We propose the use of 3D annotations as a way to meaningfuly associate the spatial representation of the 3D shape with other related information. In this way, collections can semantically be enriched providing a natural layer for presenting and interacting with additional information related to the objects in the collection. Thus, once a 3D collection is built, 3D annotations can support further applications, such as incorporating historical material; or information on the condition of the artefacts, in order to support their monitoring and preservation over time.

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The paper will describe the previous work in 3D annotation (section 2) and our proposed approach for 3D annotations and semantic propagation in the context of a CH collection (section 3). In addition, section 4 will present a case study where a semantically rich 3D collection is built with contributions from the community, in order to record the conservation state of public monuments and sculptures in a city and to enable heritage professionals to make informed decision on their conservation and preservation. Finally, conclusions and further work will be described in section 5.

2. Related Work

The use of 3D annotations is the mechanism for enriching shapes with semantic, allowing the association of relevant information with user-selected portions of the shape. The result is an annotated shape or a semantically enriched shape. This abstract view of the shape combines the geometric description, contextual information and knowledge of the represented object, as well as the created relationships. Different initiatives have been dealing with the challenges involved in this field in the last 10 years, including projects such as AIM@SHAPE [prob] and its Digital Shape Workbench [dig], Focus K3D [proc], 3D-COFORM [proa], Enhancing Engagement with 3D Heritage Data through Semantic Annotation [enh], V-MusT [prod] and Semantic Annotations for 3D Artefacts [sem]. Current trends, like 3D Internet [ABK07] or the Linking Open Data [lin] movement, are also addressing these challenges. These initiatives have highlighted that the processes involved in annotating a 3D shape for semantic enrichment is complex and manifold.

As shown in figure 1, this process usually starts with a 3D shape and involves i) defining the geometric structure of the 3D shape, ii) structuring the information and knowledge which will enrich the 3D shape, iii) implementing a mechanism to create an annotation, as well as iv) representing and storing the annotation.

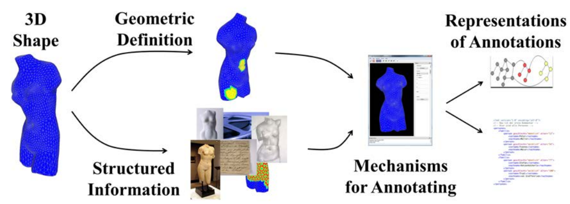

Figure 1: *Building blocks of the 3D shape annotation process.*

2.1. Geometric definition for annotating

A requirement prior to annotating a 3D shape is to understand its intrinsic structure. This is because an annotation can refer to the whole shape, a portion, multiple portions, a single point or several points on the shape. There are different techniques to understand the 3D shape ([MSSPS07], [DFMPP11]) and to formulate such a geometric definition ([SF09]), including sketching, painting, outlining, fitting, segmenting and structuring. These techniques can operate manually, semi-automatically or automatically, depending on the degree of automation and therefore of the required user involvement. A comparison of segmentation techniques and of the different principles which drive segmentation are discussed by Shamir [Sha08] and Chen et al. [CGF09].

2.2. Mechanisms for annotating

Generally, 3D annotating involves a mechanism to combine the geometric description and the information related to the 3D shape. Different mechanisms have been proposed, which vary depending on i) the application domain; ii) the degree of user intervention that they require; iii) the technology which supports them; and iv) the degree of structured information which they involve (ranging from highly structured information to free text). In its majority, most systems use semi-automatic mechanisms, which normally require a degree of user intervention to define an annotation. Examples include a mechanism to manually annotate a master 3D shape and then automatically propagate the annotations to a data-set ([SSS*10], [KHS10]). Manual mechanisms usually involve user driven geometric definition and the association of either structured information, [ARSF07], [PDF09], [FPC08], [ARSF09], [PDF10]) or free text ([HG10]). This type of manual mechanism usually requires a user interface or *annotation tool*; where a graphical user interface (GUI) allows the user to enter free text, select some text from a menu, or select an item from a diagram.

2.3. Representations of the annotation

The approach used to structure, store and transmit the annotating process output is of great relevance to the annotation's indexing, retrieval and reutilisation. Nevertheless, there is no agreed format for this. Current research indicates two main strategies for supporting the stability and preservation of the annotation:

- Persistent annotations: these store the annotation in a database based on a semantic model. The model describes the associations or relations between different media and this is built as the annotating process takes place [ARSF07], [ARSF09], [PSSD*11], [ope], [HCSVdS10]).
- Transient annotations: these store and transmit annotations in a data file. Some examples include, the use of MPEG-7 ([mpe]), VRML/X3D ([JDG99], [PG11], [PDF10]), and COLLADA ([HSB*09], [RMA09]), among other formats.

Although these and other initiatives described in the above sections have produced useful results, the technologies available to support 3D annotations do not offer an integral solution. Thus, this remains an active area of research ([HF07],

[SF09], [TSB10], [KFH10]), [CMSF11]), where different challenges need to be solved to fully support a semantic enrichment pipeline. Some of these include:

- automatically extracting information from a 3D shape;
- modelling semantic information;
- automatically linking it to the 3D shape;
- using standards to store, interoperate, and preserve annotations in the long term as only a few existing 3D data formats support semantic markups.

Our solution aims to overcome some of the challenges in this area. In particular, the focus is on using a standardized semantic model, in order to represent the annotations and their linkage to the 3D shape, such that an entire 3D collection can be supported. This solution aims to produce a semantically rich network of multimedia information, including 3D data, which facilitates the preservation and monitoring of tangible heritage.

3. Enriching 3D collections by means of annotations

In order to support the annotation of a 3D collection, we are using the Repository Infrastructure (RI) developed by Doerr et al. [DTT*10]. This integrated infrastructure supports storing and managing digital objects in an Object Repository (OR) along with their provenance metadata and annotation information in a Metadata Repository (MR). The RI can serve as a collaborative working environment to support distributed users during different heritage practices. The proposed 3D annotation mechanism is fully integrated within this solution.

In order to better convey the mechanisms and the semantic model to support annotation, we introduce the following terms:

- *Area*: it is an abstraction of positions/regions defined on different media objects, i.e. text, digital 2D images and 3D shapes. The geometric (maybe volumetric) definition of an area exists in addition to the geometric elements of the object. It does not use the vertices of the 3D shape itself.
- *Segment*: this is a subset of a 3D shape and it is an *Area* itself. Segments are generated out of manual (or automatic) segmentation processes and become objects on their own. The input 3D shape to the segmentation process as well as the result, exist as entities in the RI and are linked to each other by a segmentation event. In this way, the traceability along the process chain is guaranteed, and provenance information can accordingly be created.
- *Annotation*: it is a commented and/or classified relation between areas. Furthermore, annotations are independent from the media object underneath and its dimensionality (1D, 2D, 3D).

Since a physical object may have several digital representations in the RI, an important issue of the 3D annotation mechanism includes the capability of geometrically and semantically propagating annotations to corresponding regions in all representations that depict the same artifact along the process chain. The following sections will describe the proposed 3D annotation approach and the propagation mechanisms.

3.1. Areas as an instrument for 3D annotating

The association between 3D shapes and semantics is realized with the abstract concept of *Areas*, which is valid for any kind of multimedia objects from a semantic point of view. In the context of 3D annotations, the *Areas* can be considered points and regions on a shape, or the whole shape itself. Geometrically, we have implemented three general forms of *Areas* (as illustrated in figure 2): a) Sphere: portions of a shape around a point, b) Cylinder: portions of a shape around an axis, and c) *Segment*: portions of a shape with an irregular form. After defining Spheres, Cylinders and Segments on a shape, two types of semantic enrichment can be built: i) comments, or b) relationships. On the one hand, comments are associations between a single or multiple *Areas*, a free text input with related information, and a classification. On the other hand, relationships are associations between multiple *Areas*, describing a directed relationship (e.g. A refers to B, A took place at B, etc.).

Figure 2: *Supported* Areas *in the 3D annotation process; a Sphere for the loaf, a Cylinder for the arm and a* Segment *for the fish tail*

The creation of an annotation implies the addition of new paths into the semantic network between the involved *Areas* and thus, enabling the enrichment of the shape itself and of the 3D collection in general.

Semantically, we have implemented a unique and uniform way to define *Areas* on the variety of multimedia objects stored in the RI. We followed the approach proposed by Pena Serna et al. [PSSD*11], which described the extension of the generic and extensible METS schema [MET11] (e.g. wrap COLLADA files and W3C HTML range in METS). Trying to keep the new schema as close to the original METS schema as possible, we extended the <mets:area> element, by introducing two new attributes (AreaID and ExtMeshAreaID) and new values for SHAPE (values: COLLADA, RELRECT, RELCIRCLE, RELPOLY and EXTMESH) and BETYPE (value: DOM-RANGE).

3.2. Semantic model for 3D annotations

The Metadata Repository of the RI is based on CIDOC-CRM (ISO 21127:2006) [CDG*09] and its extension CRMdig [TTD*10] that allow to represent not only human material history and cultural objects, but also provenance metadata, annotations and co-reference information.

Our annotation model, shown in figure 3, is simple but very rich and extensible. It allows to associate parts of different media with parts of a 3D shape. These associations are classified into different categories of relationships as defined in CIDOC-CRM, which is the core conceptual schema and in its extension CRMdig. Relations can carry comments and are represented in the semantic graph for later searching and reasoning. Our concept of *Areas* eases the propagation of semantic annotations among different representations, e.g. different resolutions of a 3D shape. Since we record the provenance information in CRMdig from the acquisition event on and we relate all events (acquisition, processing, segmentation, annotation, etc.) to our internal representation of the physical object (artefact), we can always ask for *Areas* being defined on different digital 3D representations and the annotations attached.

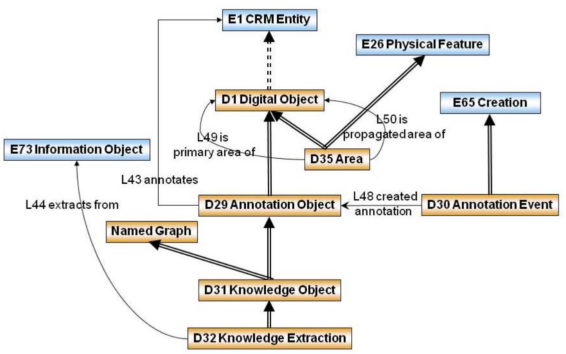

Figure 3: *Annotation model of the CIDOC-CRM schema*

3.3. Geometric propagation of annotations

For different reasons, the RI can store several different digital representations of the same CH artefact (master model, simplified derived models or edited ones, partial representation such as just the head of a full-body statue, etc.). When we define an *Area* on just one of those representations (i.e. selecting the nose to add some semantic information to this region), the capability of propagating this annotation to the corresponding region in all the other digital representations that depict the same artefact would be a very handy feature.

The semantic propagation is the action of sharing already created annotations between different digital 3D representations of the same CH object. From a semantic point of view, the UUID of the primary *Area* is shared with the corresponding *Area* on the corresponding different representations, but being considered as a propagated *Area*. However, from a geometric point of view, the propagation might be challenging, since a different resolution, a different scaling, or a different orientation could prevent the direct transformation of the *Area*. Thus, we first need to find the corresponding transformation between the two digital representations, in order to apply it to the *Area* to be propagated.

Since the propagation is triggered by the user and there is no previous information about the correspondence between the two digital representations, we implemented a simple algorithm that can be executed during the enrichment process and in an interactive manner (see table 1 for performance measurements), while providing an educated guess of the needed transformation. We find the transformation (figure 4a) by calculating a characteristic vector (figure 4b) for each shape and then by computing the corresponding rotation, scale and translation matrices between both vectors (figure 4c). The final transformation matrix is applied to the *Area* to be propagated, which is then transformed according to the characteristics of the other shape. Figure 4 illustrates the algorithm that enables the computation of the correspondence between the two shapes, provided that the shape is not symmetric and that the scale is isotropic, which are very common properties of digital CH shapes. Additionally, the two shapes need to represent the same state of the CH object, in other words, the algorithm will not produce accurate results, if one of the shapes lacks a part (e.g. an arm, head, decoration, etc.). For this extraordinary cases, a time consuming algorithm will be required, for instance *Principal component analysis* or *Scale-invariant feature transform*.

Table 1: *Performance measurements in milliseconds for the geometric propagation.*

Mesh	Vertices	Time
Grifo	752.045	63.2
Neptune	367.875	42.6
Vergine	126.176	16.4

3.4. Semantic propagation of annotations

The semantic propagation is based on a search algorithm that runs on the Metadata Repository. Thus, when a new *Area* is defined on a 3D shape, the algorithm will look backward and forward on the digital process chain, searching for other shapes that might include the same *Area* of interest, in order to accordingly propagate it. Each time an *Area* is specified on a shape, the MR is populated with the relation "<AreaID>

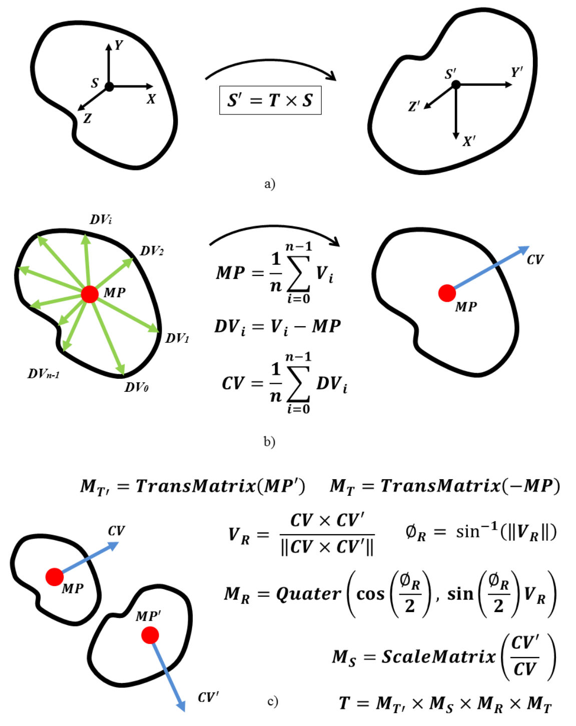

Figure 4: *Algorithm for the geometric propagation of an* Area*; a) transformation between two abstract shapes with different orientation and scale, b) calculation of the characteristic vector of a shape, and c) computation of the transformation matrix*

<isPrimaryAreaOf> <ObjectID>" or "<AreaID> <isPropagatedAreaOf> <ObjectID>", depending on the originality of the *Area*. The combination of the algorithms for semantic and geometric propagation, regarding annotations and *Areas* respectively, provide this kind of information to the RI and therefore to the MR.

Given the fact that annotations will also share the originality with the *Areas* they are declared on (if the *Area* is primary then the Annotation will be Primary; if the *Area* is Propagated the Annotation will be propagated accordingly), there is the option to display all annotations linked to *Areas* of a 3D shape or just the ones that are made on the primary *Areas* of this 3D shape. To achieve that and based on the previous paragraph, a query on the MR about the links "isPrimaryAreaIn" that refer to the current digital representation, will distinguish the annotations made on the primary *Areas* from the ones that come from propagation. There are two types of annotations to be distinguished: i) the annotations that are created by annotation events, and ii) the hyperlinks (outgoing links). Both are described in RDF files and are ingested in the MR.

4. Case Study: Supporting the preservation of sculptures and monuments by using a semantically rich 3D collection

The systematic development of semantically rich 3D collections requires of different activities from acquisition and management to the presentation of the 3D collection. This case study presents the creation of a 3D collection of public monuments and sculptures in the city of Brighton and Hove in the United Kingdom (UK) by using a crowdsourcing approach [KREP*12]. People in local communities were invited to take photographs of the objects in the collection and upload them to a website along with provenance information. By doing this, data was gathered of the same object photographed at different times to increase the amount of data that can produce a quality 3D shape, using computer vision techniques (Arc3D [VG06], 123D Catch [Aut11]).

The resulting 3D shapes were ingested into the Repository Infrastructure by means of the ingestion tool (see figure 5). This tool enables the user to input all provenance data of the 3D shape, such as source images, as well as details of the acquisition and processing stages.

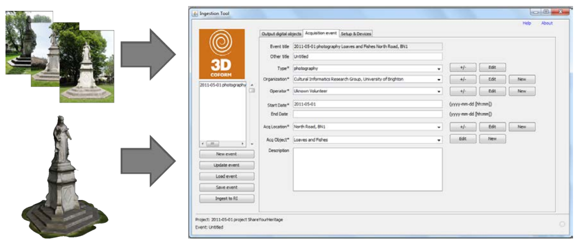

Figure 5: *Ingesting the photographs and 3D shapes generated by contributions from members of the public to the 3D collection*

In addition, legacy metadata, which had been previously recorded by the Public Monuments and Sculptures Association (PMSA) [Uni11] was mapped to the CIDOC-CRM schema and ingested to the repository using the D2R Server tool [BC06]. This included information regarding the physical artefacts, such as title, location, material, parts, and dimensions, as well as the condition assessment information.

The Integrated Viewer / Browser ([PSSD*11], [PSSRS12]) was used for the semantic enrichment. This tool allows exploring the created 3D collection, by means of querying and visualising the 3D shapes. Different options are available to search the RI, supported by complex queries, which are based on fundamental categories and relationships. For example, useful queries during this case study include: i) finding all 3D shapes, which have been produced during the crowdsourcing exercise, or ii) finding all virtual surrogates from the city of Brighton.

Once the relevant 3D shape is found, the tool enables to visualise and to enrich the 3D shape with semantic relationships. The interface, shown in figure 6, allows for visualising and inspecting the 3D shapes, for creating *Areas* on the 3D shapes, and for commenting *Areas* or building relationships between different *Areas* (annotating). The interface is divided in three main sections: i) the 3D viewer with the functionality for defining *Areas*, ii) the annotation tools, and iii) the metadata window with information on the multimedia objects. The tool supports different multimedia objects, for instance pieces of metadata, images or 3D shapes, which are arranged in a working window (for defining *Areas*) and a collecting window (for comparing and selecting additional multimedia objects). This feature supports the propagation from one object on one side to the other on the other side.

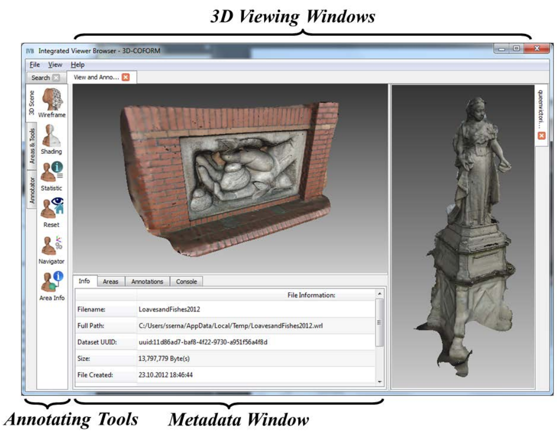

Figure 6: *Annotation interface for semantically enriching 3D shapes*

One of the aims during this case study was to enrich the resulting 3D collection, in particular specific regions of the 3D shapes with condition assessment information - available from the legacy metadata. Normally, this information is recorded in a text based format, hence heritage professionals accessing this information need to understand to which part the text is referring to. Some examples which illustrate this issue include: "The surface condition is poor with pitting and erosion of the stonework", "Cracks to surrounding arch", and "The structure is severely weatherworn, particularly on the side facing the sea". Common problems of using a text format to describe condition details is the lack of specificity of the language (e.g. which area of the stone work?, or which area surrounding which arch?), as well as the lack of contextual information from the reader's perspective (e.g. which side of the object is facing the sea?). Therefore, linking this information with a 3D shape provides a better and more accurate overview of the object's condition. This solution has the potential to provide heritage professional, looking at the preservation of these monuments and sculptures, a more effective tool to assess their risk and take further actions if needed.

Thus, the functionality of the tool is used to link condition details to the 3D shape. The example in figure 7 illustrates the "Loaves and Fishes" object in the city of Brighton UK, which condition assesed in 2007 indicates that "Some biological growth at the bottom of the side facing the road" affects the monument. The user can annotate this 3D shape by:

- Searching for the condition details in the legacy metadata of the 3D shape and loading this information into the tool (see left area of the interface shown in figure 7).
- Selecting the section of the geometry to which the condition detail text refers to. For this, the three different types of shapes described in section 3.1 (see figure 2) can be used. The algorithm behind the latter operation looks for a feasible feature on the 3D shape after each mouse click, in order to facilitate the specification of the segment. By default one area is created, which defines the whole 3D shape. Once the Area is created, it is included in the sheets with its associated metatdata. The right window (collecting window) of the interface shown in figure 7 shows a red cylinder delimiting the location of the condition.
- Annotating the selected *Area(s)* of the 3D shape. Two different types of annotations are supported, which involves linking the area to: i) free text; or ii) source data stored in the repository, which can respectively be metadata itself or another area of a multimedia object. This operation involves using a simple drag and drop mechanism. Once the annotation is created, this is automatically ingested into the repository. The bottom section of the interface in figure 7 shows how a relation is established between the *Area* in the geometry and the legacy metadata.

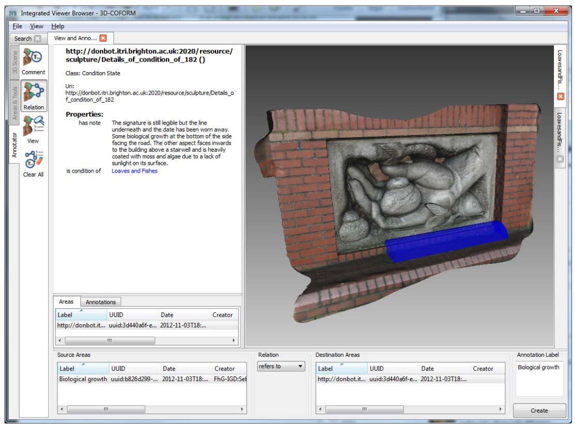

Figure 7: *Example of area definition in the 3D shape and its enrichment with condition assesment information*

Furthermore, the crowdsourcing mechanism enables the generation of several 3D shapes representing the same object at different times. This is important for documenting the condition of the objects, as this type of tangible heritage is not static. On the contrary, the condition of sculptures and monuments changes all the time due to different causes, such as weather conditions, contamination levels, heritage crime, or preservation work. Hence, it is important to document these changes when up-to-date 3D shapes are generated and ingested for an object already stored in the repository. For this, the propagation capabilities are fundamental, as they allow to automatically propagate an annotation to all other representations of the same object in the repository.

The user can propagate the annotation of the annotated 3D shape by opening both, the old and the new version, and by selecting to propagate a selected annotation. The *Area* (red cylinder) along with its relationship to the condition details is then propagated to the new 3D shape, as shown in figure 8. It is also possible to add free text to update the condition details, in case these have changed. For instance, during 2012 the "Loaves and Fishes" was cleaned. Hence, a new comment was added specifying this change.

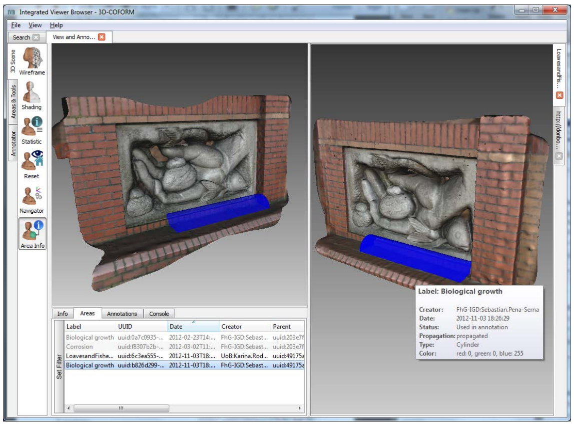

Figure 8: *Process for propgating an annotation to newer 3D shapes.*

The propagation functionality allows newer 3D shapes in the repository to keep a historical record, tracking all changes suffered to the represented objects by keeping all propagated annotations made to the object. This functionality further enhances the ability of heritage professionals to understand the required preservation efforts for a monument or sculpture.

Furthermore, the reconstructed 3D shapes, the collected metadata on the digitisation processes, as well as the legacy metadata used to enrich the 3D shapes, are stored in the RI at this stage. Thus, additional applications for disseminating and visualising this information are possible.

5. Conclusions

This paper has presented research results on the semantic enrichment of digital 3D shapes, which supports the working practices of cultural heritage professionals. The proposed mechanisms for describing, creating and propagating 3D annotations to a full collection represent clear advances in the field of 3D documentation.

The case study of enriching a 3D collection produced by contributions from the public, in order to document the condition details of the tangible heritage, illustrates only one real example of the different applications of this technology. Hence, it can be concluded that semantically enriching 3D content has a great potential for enhancing heritage applications, as well as for making 3D content available to interact with other applications based on semantic networks.

Nevertheless, many research challenges remain unaddressed. Further work involves automating shape segmenation, enabling the automatic forward and backward propagation of annotations, and the development of new interfaces, which can spatially visualise the annotations and their semantic interconnections.

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