3D Reconstruction of Cultural Heritage Artifacts

A Literature Based Survey of Recent Projects and Workflows

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3D modeling technologies have gained importance as tools for the reconstruction and visualization of Cultural Heritage artifacts during the last decade. But there is still only little systematic research about how and for which purposes these technologies are used. Further on from a methodological perspective, it would be necessary to understand how 3D modeling is affected by disciplinary boundaries and challenges specific to historic topics. For the investigation of these topics, the authors have completed a content analysis of 478 conference papers and articles related to 3D reconstruction modeling in the field of humanities. The main objective was to identify current topics, technologies and institutions involved. Most of the projects described in those publications dealt with data acquisition and model building for existing artifacts. Only a small number of projects focused on structures that no longer existed physically. What are the current trends regarding 3D reconstruction of Cultural Heritage artifacts? On the one hand, there are many individual projects using 3D technologies to reconstruct historic items. Research shows that such reconstructions are most commonly used for presentation, research purposes and sometimes for digital conservation of large buildings or city models and often realized by interdisciplinary workgroups. In the implementation process a wide scope of technologies is used and new technological developments are quickly adopted as well as current socio-technological trends like crowdsourcing or mobile computing. On the other hand these projects are mostly prototypic and an implementation as everyday technologies is still in progress. There are many efforts to handle this challenge. Nowadays, large scale funding schemes, international networks and research facilities support the development of cost efficient tools, workflows and standards. Beside these findings, the authors identified a vivid scientific community and their protagonists. Since 3D is becoming a common and easily accessible tool for historical reconstructions, issues such as quality standards, compatibility, sustainability and requirements of focus groups are increasingly prominent in academic discourse, but were implemented in only a few practical projects so far.

3D Reconstruction and Cultural Heritage

When determining Cultural Heritage as a sum of remaining items traded from former times, 3D modeling technologies offer a chance not only to digitize historic artifacts which are still extant but to reconstruct even objects virtually, which are no longer extant physically but only known from descriptions. Until the year 2000 3D visualization of cultural heritage artifacts was used merely as digital replacement for physical models.[1] It is only since the new millennium that a wider usage has occurred. Nowadays 3D models are mainly used to visualize historic items to the public as well as for research purposes and for education.[2] Beside that there are many other purposes for 3D technologies like Cultural Heritage Management and conservation tasks, research or even advertising. In most of the cases researched 3D models had not been created for one of these purposes alone but also for focusing on various objectives. Workflows for a virtual reconstruction of extant artifacts are mostly technologically or logistically challenging, but a virtual reconstruction of no longer extant objects adds tasks like an interpretation and inclusion of describing historic sources. While especially for these interpretation tasks archaeologists and art historians are involved, there are – as we will analyze closer due this investigation – many scientific disciplines dealing with a 3D reconstruction of cultural heritage content.

Methods

There have been many investigations to determine the use of 3D for Cultural Heritage as a field of research during the last years.[3] One of the latest and most elaborate examples was the EU project EPOCH, which finished in the year 2008.[4] The project involved many leading European institutions and protagonists analyzing a current state as well as future perspectives and challenges. Another long term research project is VIA, which is surveying and supervising the workforce and cooperation in the field of archaeological illustration in Britain.[5]

Research Objectives

While most of these investigations focus on certain aspects, there has been little systematic research especially for 3D reconstruction based on empirical findings until now. Our main objective was to sketch a current state based on an empirical analysis of recent publications. What are our research questions? On the one hand our research interest deals with the current usage of that technology. This includes the question for current use cases, workflows, collaboration and standards. On the other hand the question was for a scientific community and its discourses. Topics inherent are institutions, protagonists and current academic discourses.

Analysis

To cope with these challenges we performed two stages of analysis: the first stage was a content analysis for publications to examine current usage scenarios, protagonists, field of research.[6] To enable a selection of relevant publications experts were asked to examine the most valuable conferences and publications. As scope for conference proceedings whole volumes were included, and an identification of relevant journal articles took place via keyword search. All publications included had to be written in English and be made available online. In our analysis a sample of 452 journal articles and conference proceedings were included during this first stage. Most of the projects described in those publications dealt with data acquisition and model building for existing structures. Only a small number of projects focused on no longer extant architecture. That kind of project in particular seems to be interesting for a study of the linkage between digital technologies and traditional humanities. To examine this linkage the authors applied a qualitative Grounded Theory analysis with a sample of another 26 international publications dealing with a reconstruction of no longer extant objects.[7]

Publication	Volume
3DArch Conf.	2005-2009
CAA Conf.	2007, 2009
VAST Conf.	2003-2007, 2010
Imaging Ancient Rome Conf.	2006
Virtual Palaces Conf.	2012
Journal of Cultural Heritage	2000-2011
Various project reports dealing with no more extant objects	1999-2011

Table 1 – Sample.

How valid are results from such an empirical analysis? Focusing on potential lacks, beside sources of error depending on data mining and empirical evaluation methods, publications generally more often than not represent academic activities and less a situation of commercial institutions.

Findings

Authors and Cooperation

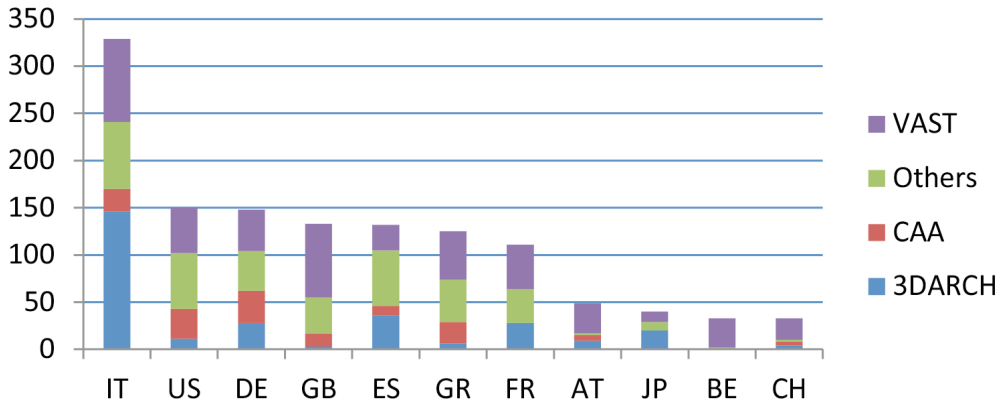

Fig. 1 Nationality of authors.

Data for an identification of an author's nationality was taken from the correspondence addresses noted in the publications. The most named nation is Italy with a percentage between 15% and 60%. Altogether authors in this sample are affiliated to 38 nations, a high quota is located in Europe. With regard to their respective disciplines, most authors are affiliated to institutions dealing with computing. This quota widely spreads between single conferences, i.e. roundabout 70% of VAST presenters are affiliated to computing institutions.[9]

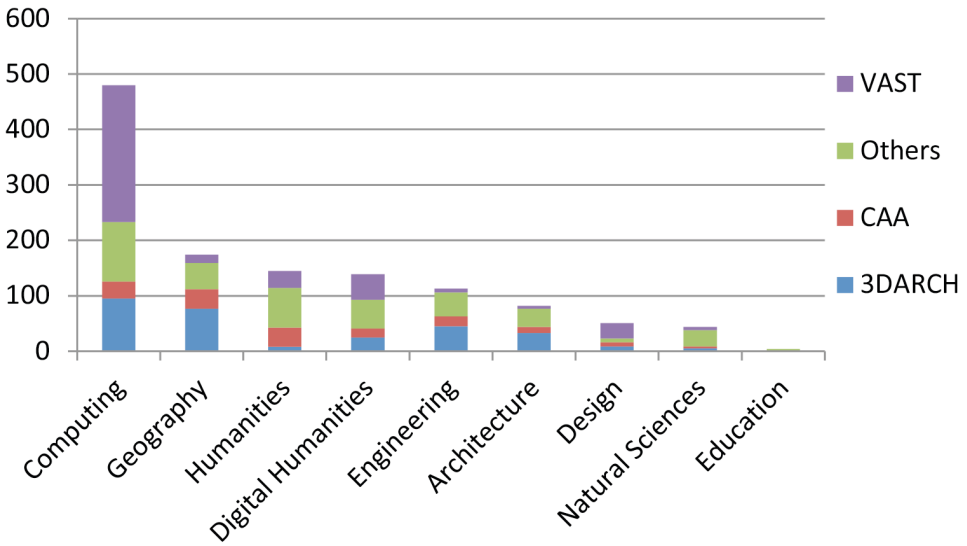

Fig. 2 Disciplinary affiliation.

Another hypothesis was that collaborative publications would inherit a knowledge communication between authors. Depending on sociological role theory, there are certain members in social communities who play an important role for sharing and broadcasting information especially across disciplinary and national borders.[10] To identify these protagonists or *multipliers* and a scientific network we performed a social network analysis.[11] Nevertheless, such information transfer is just assumed and there are no possibilities to reconstruct intensity or even an existence of information transfer between authors from data.

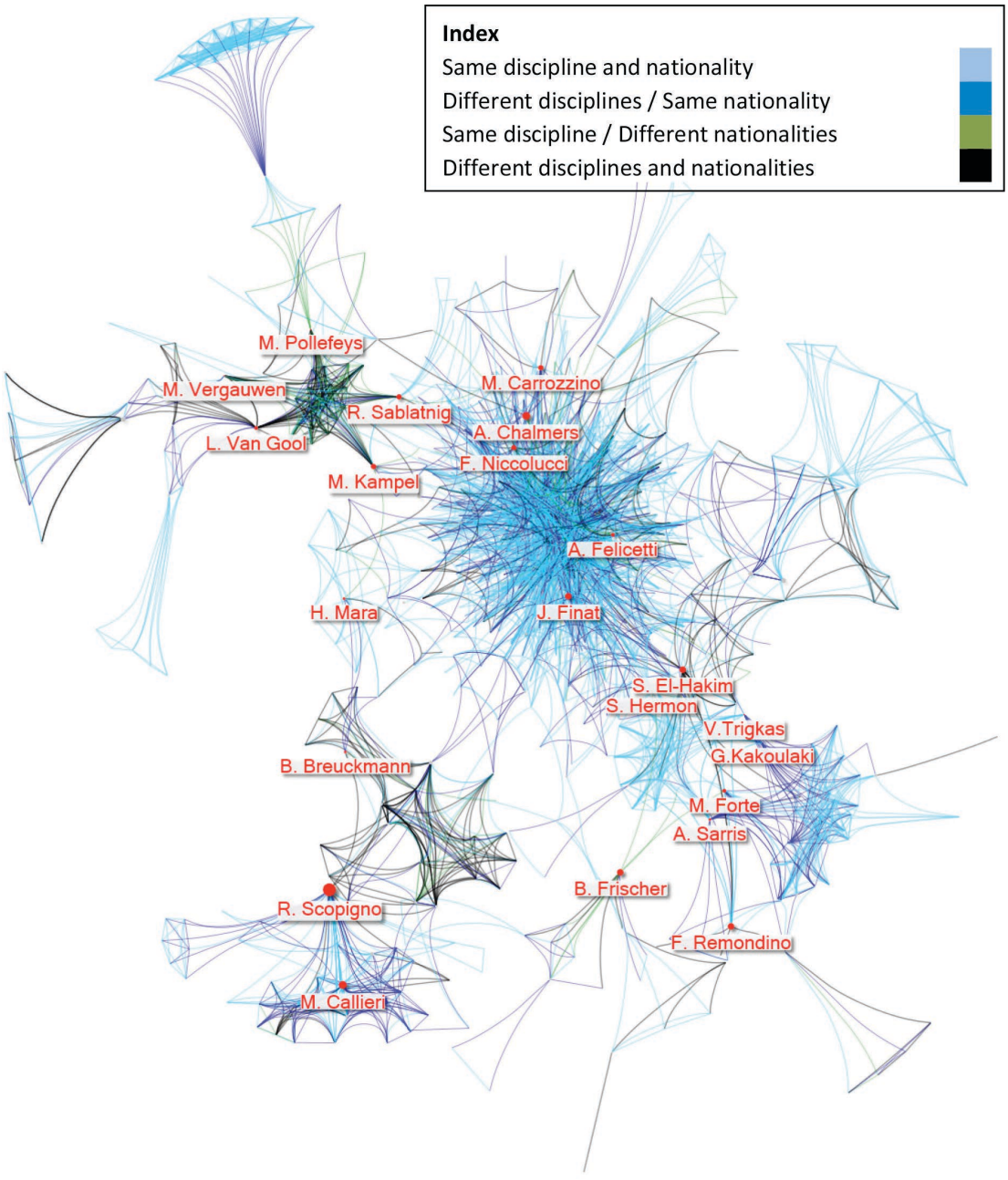

Fig. 3 Author-co-author relations (multipliers highlighted).

Publications have been written by 1500 persons and containing over 3000 links between authors of cooperative articles. Most of the publications have been written by authors belonging to the same discipline and nationality. But there are also several international or interdisciplinary networks visible whose members have written more than just one common publication. Also some important multipliers could be identified, which connect groups of researchers to each other. To validate, results were discussed with experts, too. Generally these multipliers identified are not only active publishers but often key role players in community in other ways, too, i.e. as members of scientific committees, as conference chairs or as initiators or leaders of projects.

Topics and Methods

Another research interest was to identify current conference interests and content of contributions. To examine this we included a sample of 339 articles in conference proceedings.[12]

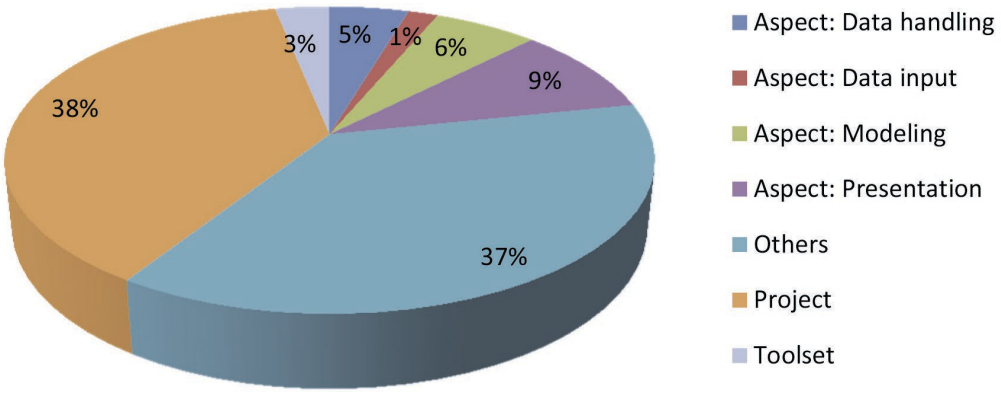

Fig. 4 Proceeding themes (n=339).

Over one third of conference contributions (37%) neither deal with 3D modeling nor historical objects. Nearly the same quantity of articles are reports about single reconstruction projects. This means that they describe workflows to reconstruct certain historic items as 3D models. Another group of contributions deal with certain aspects of 3D reconstruction for historic purposes like presentation and modeling strategies, data acquisition methods or a handling and classification of 3D data. Focusing only on project reports, there are two main strategies for reconstruction, depending on whether the object to be reconstructed is still extant.[13] In case of still extant objects a digitization mostly takes place via data acquisition and algorithmic model building. For acquisition various technologies are used, depending on the type and proportions of

the item, i.e. photogrammetry, laser scanning, LiDAR (light detection and ranging) or for specific purposes even magneto resonance acquisition or even computer tomography.[14] More than 2/3 of project reports deal with such a combination of data acquisition technologies and automated model reconstruction for extant objects or its fragments.

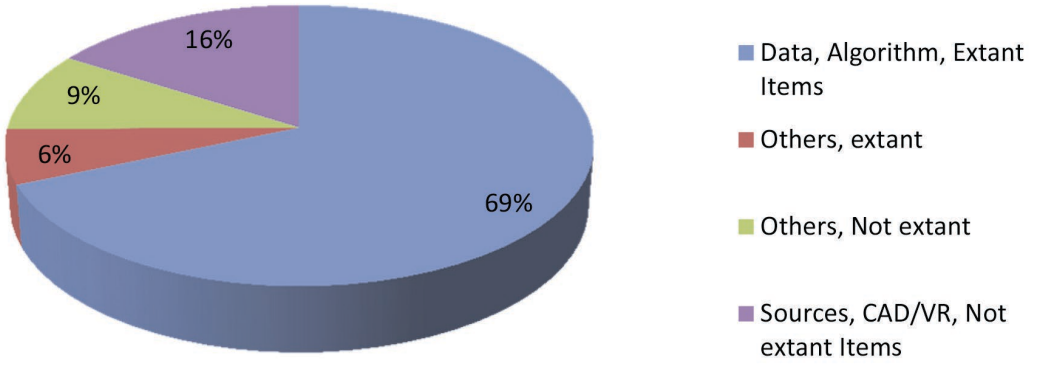

Fig. 5 Project reports (n=175).

A proportion of 16% deal with a reconstruction of no longer extant objects from historical sources. In these cases a model creation takes place via VR or CAD modeling.[15] Technical workflows for the creation of these models have been similar for more than a decade,[16] but output quality and tools have changed rapidly. Most of these projects are realized by interdisciplinary teams using standardized 3D software for model building. While output qualities and inherit sources are widely depicted in publications, the research of interdisciplinary cooperation during these projects is still lacking. Beside these main types there are several projects where, for example, data driven automated reconstruction is used to reconstruct no longer extant objects. Objects reconstructed by these projects are often architectural structures or arts, mostly religious buildings like churches or temples. Most items are located or originated in Italy, Spain or Greece. With regard to the time of origin of these objects, most projects deal with content from the Roman, late medieval or modern times.[17]

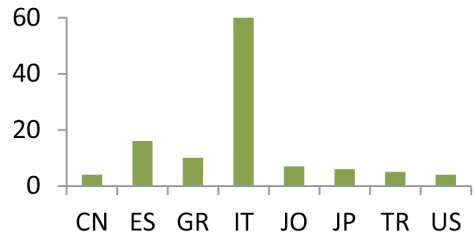

Fig. 6 Location of artifacts (top 8).

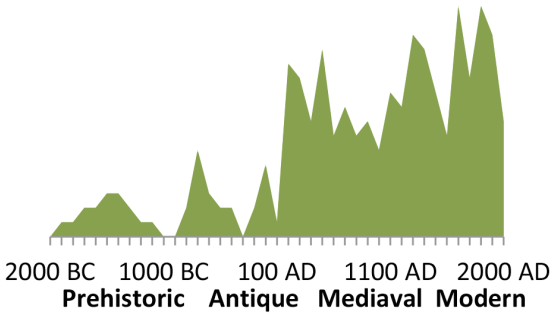

Fig. 7 Time of origin of artifacts.

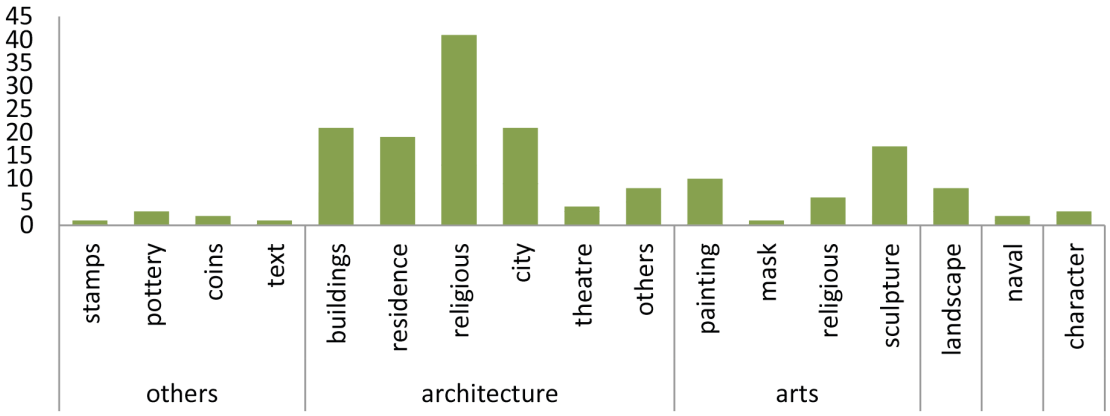

Fig. 8 Types of artifacts.

Workflows

While a reconstruction of still extant objects is challenging for mainly technical aspects like complete and accurate data acquisition and handling or an efficient and comprehensive algorithmic model creation, technical workflows for a VR or CAD modeling of no longer extant objects are widely established and similar to other 3D modeling tasks like engineering and design. Specific challenges for such interpretative reconstructions are more a case of coping with historic sources or interdisciplinary workflows.

Input[18]			
	Historical sources	Historical pictorial sources	*i.e. ground plans, panorama*
		Additional historical sources	*i.e. documents, eye-witnesses, coins*
	Contemporary sources	Contemporary pictorial sources	*i.e. plans, photography*
		Data sources	*i.e. laser scan, photogrammetry, GIS*
		Additional contemporary sources	*Findings, research output*
	Logical implication	Architectural systems	
		Analogies	*As "Comparison to similar objects"*
		Inner model logic	
Modeling			
	Automated	Algorithmic modeling	
	Semi- automated	Rule based modeling	*i.e. Procedural generators, Construction kits*
	Manual	CAD/VR modeling	
Output			
	Static		*i.e. Illustration*
	Dynamic		*i.e. Animation, Audio visual Presentation*
	Interactive		*i.e. Augmented Reality, Web Application, Games*
	Physical		*i.e. Rapid molding*
	Data		*i.e. FEM-Analysis*

Table 2 – 3D reconstruction process – taxonomy.

Especially the quality of sources highly influences the validity of resultant models: especially for no longer extant objects historical sources or contemporary remnants seldom deliver all information required for a reconstruction. To attain a coherent model many decisions are based on logical implications like analogies to similar objects, requirements of an architectural system such as the Vitruvian system, or simply on inner-model logic as with common boundaries of modeled parts.

Acquired data, which is mostly available for extant objects only, gives the opportunity to build models in a highly automatized way via algorithms. For such modeling methods there is currently a lot of research and development to reach fast, reliable and flexible algorithms. But also

for the modeling of no longer extant objects, which is mostly done in traditional CAD/VR matter, there is some effort to automatize certain process aspects. An automated form of processing of logical implications is focused on in some projects going as far as libraries of pre-constructed parts used in some construction kits.

Another closely related issue is quality management during the modeling process.[19] One important strategy is to set up guidelines for workflows which are related to process or model quality. Depending on the type of input data, model related guidelines define a level of accuracy to be achieved or criteria for a selection of objects to be reconstructed and a level of detail necessary. Process related guidelines define rules for workflow, i.e. for transparency, to conform to 'Good Scientific Practice'. Closely related to that are strategies for quality assurance. There are two main strategies described in papers, on the one hand external committees like boards of experts, on the other hand internal editorships involving a board of team members and ensuring quality via audits.

As figured out in the beginning of this article, there are many different purposes for such 3D models which highly influence type and quality of output. Most important are depictions of these virtual models, either as static pictures, such as illustrations or in a dynamic form like animation and increasingly their use in interactive applications, too. One important issue is that such output is mostly visual oriented but some projects also focus on multi-sensual outcome from such 3D models, including, for example, aural impressions. In other cases a 3D model would be used as data input for other analytic steps, for example to perform FEM (Finite element method) analysis or hydraulic simulations, or to create physical prototypes.[20]

Implications

What are the current trends and discourses to be found in current publications concerning the use of 3D technologies for digital heritage?

On the Way from Prototypic to Daily Use…

Hitherto most 3D reconstruction projects have been prototypes and an implementation as everyday technologies is still in progress. There are many efforts to handle this challenge. During the last years large-scale funding schemes, like the EU ICT grants, support the development of cost efficient tools, workflows and standards.[21] Also at conferences many contributions report about such cost efficient and easy to use strategies. But nevertheless, currently most of the tools developed or workflows presented often either offer highly automated workflows for very special use cases, or still need IT-skilled operators and manual operations.

Fast Adoption of New Technologies

There have been many technological developments during the past few years for 3D modeling and visualization. Generally these inventions are speedily adopted for cultural heritage purposes, too. In publications there is a huge range of technologies described which are used or sometimes 'abused' for such purposes, i.e. medical computer tomography[22] for data acquisition or CAVE-like environments for visualization. Also modern technological trends like Smartphone or Web 2.0 are quickly adopted as well as current socio-technological trends like crowdsourcing[23] or mobile computing.

Standardization, Sustainability, Sharing?

While such adoption of modern technologies and trends mostly occurring in a prototypic way, aspects for standardization of quality, compatibility, sustainability and requirements of focus groups are increasingly prominent in academic discourse, too. For a creation of 3D models there have been many prototypic workflows, guidelines and strategies developed as well as conventions for presentation and visualization.[24] Nevertheless, these guidelines are implemented for single projects only, especially regarding the reconstruction of no longer extant objects.[25] A similarly situated aspect is a documentation of the models created. While Metadata as a standard for documentation seems widely accepted in academic discourse, there are many different classification schemes fostered by their inventors and no unified standard seems in sight.[26] While the documentation of the project outcome is often discussed, the documentation of the creation process itself is very seldom thematized.[27]

Institutions: Digital Humanities and Knowledge Networks

As figured out there are many players like international networks and research facilities dealing with 3D Cultural Heritage content. In publications researched, academic institutions like universities or research facilities with various disciplinary backgrounds are often named. Beside that there are an increasing number of institutions or networks specialized in 3D Cultural Heritage topics, i.e. Digital Humanities research facilities or commercial institutions. But at the moment these are still less prominent in publications.

Beside these institutions a considerable amount of cooperation networks have been funded during the last years. This means disciplinary societies like *Computer Applications & Quantitative Methods in Archaeology (CAA)*, societies and infrastructures dedicated to certain aspects of education, standardization or coordination like *Europeana, DARIAH* or *PALATIUM* as well as communities of practice like the British *Computer Vision Groups*.[28]

Presentation and Publication

Another topic which is prominent in academic discourse is the question of presentation. Actual discourses favor a user friendly presentation look, with a main discourse about photorealistic presentation vs. non photorealism. Another trend is to move on from a presentation of static artifacts to complex and lively impressions of history, involving enhancement of visualization with dynamic elements like crowded places.[29] Other trends are concerned with a presentation of content. This includes an increasing use of interactive Web presentation environments like Google Earth,[30] as well as a materialization of virtual 3D models via rapid prototyping methods or multi sensual presentation possibilities.[31]

Summary

Are research questions answered? At a glance 3D technologies are widely established and used in many reconstruction projects for Digital Heritage artifacts. Especially statues and buildings in Mediterranean countries dating from all periods AD deliver rich content for such reconstruction. Also there is an evident scientific community involving researchers from various disciplines and many countries, whereby computing as a discipline and Italy as a country are most prominent.

While new technologies and trends are quickly adopted, an implementation as every-day technology for cultural heritage purposes is still in progress. Fields of this work are a development of cost effective and easy to use tools and workflows as well as a definition of common standards or an enhancement of cooperation and education. While these topics are prominent in academic discourse and funding objectives, a wide implementation in practical projects is still outstanding. Irrespective of the wide scope of research for 3D technologies there are still several outstanding topics like an investigation of interdisciplinary cooperation workflows, a scientific reconstruction of complex, dynamic systems or proven educational concepts for the training of historians or archaeologists in the use of 3D technologies.

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Illustrations

Table 1-2 and fig. 1-8 Authors.

[1] Novitski 1998.

[2] Greengrass and Hughes 2008.

[3] Frischer 2008.

[4] Arnold and Geser 2008.

[5] Gibbons 2012.

[6] A short version of this paper will be published in: Münster and Köhler in print. For methods see: Mayring 2000.

[7] Münster 2011.

[8] Selection of important articles took place via Keyword based search.

[9] For 21% of authors the respective disciplines at affiliated institutes could not be identified or not distinguished precisely.

[10] There are several studies on scientific communities and inherent social interaction, i.e. Stützer et al. 2011.

[11] For methodology see: Wellman 1988.

[12] Because a search of relevant journal articles took place via keyword based search, these articles had been left out.

[13] A similar classification schema, distinguishing both, modeling workflows and qualities of measurement: De Francesco and D'Andrea 2008.

[14] Pavlidis 2007.

[15] Stojakovic and Tepavcevic 2009, Koller et al. 2006.

[16] Masuch 1999.

[17] Many projects do not reconstruct objects from one certain age only but various time slides or an evolvement over time. For projects which deal with content from different centuries each century affected was counted.

[18] C.f. Hermon 2008.

[19] As one approach to quantify such problems: Hermon et al. 2006.

[20] Grellert and Haas 2016.

[21] http://3dcoform.eu/index.php#&panel1-1, accessed on 21 May 2012.

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[23] One example for Crowdsourcing is the 'Castle Construction Kit': Gerth et al. 2005; Wagener, Seitz and Havemann 2016.

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[25] Niccolucci et al. 2010.

[26] An elaborated compendium for Metadata standards: Becker and Riley 2010.

[27] For example: Pfarr 2009.

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[31] Erving, Rönnholm and Nuikka 2009.