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Introduction

The accurate registration of observations in the field is an important activity during archaeological fieldwork. In many archaeological projects, two-dimensional geographic information systems (GIS) and relational databases are being employed to store these data.[2] In many cases, this method of documentation is sufficient. However, when complex monumental sites are concerned, of which large portions are still standing, a two-dimensional approach is not adequate. It requires much imaginative power of the researcher to analyse the relations between objects and structures of a three-dimensional nature in a two-dimensional system. A 3D GIS could offer a solution for this problem. Although the use of 3D technologies in archaeology has greatly increased over the past decennia, only a few archaeological projects are known to have been working towards a 3D GIS.[3]

This article presents the steps that have been taken to develop a 3D GIS for 'Mapping the Via Appia'.[4] This project investigates the area around the fifth and sixth miles of the Via Appia Antica (fig. 1). In antiquity, the Via Appia ranked as the most significant route from Rome to southern Italy. The road was constructed from 312 BC onwards, and has seen many changes since.[5] In antiquity, the Via Appia was an area flourishing with various cultural, economic, and religious activities, of which physical traces remain nowadays in the form of funerary monuments, villas, sanctuaries and farmsteads. In medieval times, the areas around Rome fell into decay. The ancient remains were reused or fell victim to treasure hunters. Round 1800 it was decided to protect the landscape of the Via Appia, and to organise it as an archaeological area. Landscape architects and artists were commissioned to rearrange the area, resulting in new landscapes and reconstructions of sometimes dubious quality.

'Mapping the Via Appia' aims to gain an insight into the Roman interventions in this suburban landscape. Applying multiple archaeological methods (excavations, archive studies, field surveys, remote sensing techniques and geophysical prospection), it makes a thorough inventory of the archaeological remains from all eras. This inventory serves as a basis not only for scientific analyses of the use of the road and its surrounding areas in ancient times, but also for present-day heritage management and the planning of future interventions. Concerning the size, complexity, and nature of the research area, a 3D GIS could play a significant part in the analysis and preservation of the data.

This article presents the pipeline that has been developed for the 3D GIS of the 'Mapping the Via Appia' project. In order to identify the needs that the system will have to cover, it starts with an analysis of the user requirements, which will then be converted into the technical implementation. A distinction has been drawn between data collection, data processing, and the development of analytical tooling. The article provides insight into the complex technical steps that have to be taken in order to create a 3D GIS that can be used for analyses. Besides, it describes applications that can be developed in the future if an open and standards-based data infrastructure is being used.

User requirements

In the initial stages of the 3D GIS development, potential users of the system were interviewed.[6] Based on these conversations, a set of user requirements has been defined.

- The measurements need to be accurate. The analysis of the various archaeological objects requires precise measurements and comparisons. A margin of 5 cm at most has been determined.
- The 3D GIS must enable researchers to query the set of objects according to features such as date, material, decoration, and size. The selection and filtering of objects based on attributed data can provide insight into spatial distribution, which contributes to the interpretation and reconstruction of the archaeological structures.
- The 3D GIS must contain the possibility to position historic images within the virtual 3D environment. Through the ages, the Via Appia has been the subject of numerous paintings, drawings and photographs, which has resulted in more than three centuries worth of visual material. By positioning these pictures within the virtual 3D environment, the relatively recent changes within the landscape and its archaeological objects can be determined.
- Since the project's team consists of members from different universities and institutes, it is crucial that the system can be used from multiple locations at the same time.
- The 3D GIS should have the possibility to integrate 2D GIS data. The various activities within the 'Mapping the Via Appia' project generate two-dimensional GIS data like georeferenced historic maps and aerial photographs, excavation drawings, remote sensing data, and geophysics data. The spatial combination of these data with the 3D data contributes to the archaeological analysis.
- The 3D data of the 3D GIS serve as the basis of archaeological 3D reconstructions of the objects surrounding the Via Appia. Therefore, it should be possible to export these data to existing 3D modelling software.[7] In order to enrich the 3D GIS with archaeological 3D reconstructions of monuments and architecture, it should also be possible to import 3D models.
- Ultimately, the system must be organised in such a way that the data will be available and usable in the long run, and that they can be integrated with other infrastructures for heritage management and valorisation purposes.

In order to transform these requirements into technical implementations, a distinction has been made between the data collection, the data structure and the analytical tooling. Table 1 provides an overview of the user requirements and indicates focal points in the development of the 3D GIS. The collection of the data, the data structure, and the tooling are components of the pipeline for creating the 3D GIS.

Data collection and processing

Data collection

Various techniques are applied in order to measure and capture the monumental sites in the area directly alongside the Via Appia. First of all, a 2D footprint of each site is measured with a differential GPS.[8] These footprints are stored as polygons, to which identification numbers (IDs) are attributed. This ID enables relation to other data sets.

During fieldwork, the archaeological sites are studied closely. Features such as material, construction technique, decoration, and date are documented in a structured manner and stored in a relational database.[9] A distinction is being made between 'sites' and 'objects'; a site consists of one or multiple objects. In order to enable easy sharing of this relational database and integration with the 3D GIS at a later stage, conversion of this database to PostgreSQL is part of the pipeline.[10]

In order to generate an accurate 3D data set, a combination of range-based modelling (laser scanning) and image-based modelling (structure from motion) is being used. As for the former, the size of the research area led to the use of Fugro's DRIVE-MAP application. DRIVE-MAP is a dynamic laser scanning application that consists of a 360° laser scanner, a panorama camera, a metric camera, a GPS, and accelerometers, all mounted on a car.[11] This scan results in a scaled and coloured 3D point cloud with xyz measurements that are related to the earth's surface (fig. 2). The point cloud has a relative accuracy of ca 1 cm. This means that the measured points have a maximum error of 1 cm in relation to each other. As for the exact location, the DGPS has an error of ca 10 cm. This accuracy is well within the limits that are set for 'Mapping the Via Appia's' goals.

Since DRIVE-MAP can only obtain data from its position on the road, the rear sides of the monuments are not present in the point cloud. In order to create a complete model, a separate point cloud is produced of each object using Autodesk 123D Catch.[12] 123D Catch is based on structure from motion technology. The software applies photogrammetric algorithms to a series of stereo photos, thus computing a point cloud. Simultaneously, 123D Catch provides textured meshes.[13] To put it simply, the creation of a mesh is like draping a blanket over the point cloud. Surfaces are computed between the points, based on various interpolation methods. To enhance the realism, the original photographs are projected onto the surface as a texture.

Processing the data (post processing)

To scale and align the 123D Catch models to the DRIVE-MAP point cloud, the open source software CloudCompare is used.[14] This software has functionality to semi automatically align point clouds. After the user has roughly scaled and positioned the 123D Catch point cloud, CloudCompare can automatically align it to the DRIVE-MAP point cloud. The software identifies common shapes in the point clouds, and merges them. CloudCompare can only process a limited amount of points, and is therefore unable to visualise the entire DRIVE-MAP point cloud at once.

Because of this problem, a script has been developed that saves a selection of the DRIVE-MAP point cloud in a separate file, which can be imported in CloudCompare.

This selection is based on the 2D footprints of the archaeological sites. The footprints, together with the DRIVE-MAP point cloud, have been imported in a PostgreSQL database with PostGIS extension.[15] The database provides tooling that enable scripts and software to manage various analytical functions. The script combines the footprint polygons and the DRIVE-MAP data set, and thus generates a sample from the DRIVE-MAP point cloud.

In order to be able query the sites and objects that have been identified in the field, the relational database needs to be linked to the objects that are defined in the virtual 3D model. However, the combined DRIVE-MAP and 123D Catch point cloud does not yet contain archaeologically defined 3D objects; it consists purely of xyz points and meshes.

To define the archaeological objects in the 3D model, a visualisation system developed by the Centre for High Performance Computing and Visualisation (HPC&V) of the Rijksuniversiteit Groningen is used. This system is based in the open source toolkit OpenSceneGraph (OSG).[16] This OSG application contains tooling to define 3D objects by means of bounding boxes. This creates a new data set of the defined 3D areas.

Implementation of analytical functionality in the 3D GIS

In order to be able to analyse the data in 3D, a visualisation and analysis interface has been developed based on the OSG application by HPC&V. The original application already contains some functionalities that are on the list of user requirements for the 'Mapping the Via Appia' 3D GIS, such as measuring in 3D space (fig. 3), import and positioning of common 3D model file formats, defining 3D objects, and the positioning of images in the 3D space. For this project, specific additional functionalities have been developed, such as the simultaneous use of the system from different locations and the possibility to query the 3D data based on the fields in the relational database.

A synchronisation approach has been applied in order to enable researchers to use the system from multiple locations at the same time. The application is installed on each individual computer and receives the data from a dedicated server. Because of the size of the dataset, estimated to be ca 40 GB, communication with the server is synchronisation-based instead of streaming-based. At the start of each first session on each computer, all data is downloaded from the server. Before each following session, only the changes will be synchronised.[17]

The functionality of querying the sites and objects is based on a link between the relational database and the 3D bounding boxes. In case one wants to know which objects are defined as travertine from the second century AD, this question is delivered as a statement to the relational PostgreSQL database. The outcome is a series of site IDs and accompanying object IDs, which are related to the corresponding bounding boxes. The 3D bounding boxes in question are illuminated in the OSG application. The point cloud and meshes only have a visual function (fig. 4).

A functionality in the list of user requirements that has not yet been implemented in the application, is the possibility to add 2D GIS data from the various research components of the 'Mapping the Via Appia' project. Given the development of osgEarth, this might well be easily realisable in the near future. OsgEarth is a development within the OSG community that focusses on the integration of OSG and geographical data. The integration of standardised GIS services for instance is one of the goals.[18] Since the 2D research data of 'Mapping the Via Appia' have already been stored according to such standards in a protected section of the Geoplaza infrastructure, which is hosted by the VU library, these are expected to be easily integrated into the 3D GIS in a later stage.[19]

The pipeline for the 'Mapping the Via Appia' 3D GIS

The various steps of collecting and processing the data that can then be analysed in an interface are shown in fig. 5. This pipeline shows the complexity of the steps that need to be taken in order to get from data to an analytical tool. One of the most significant findings that have occurred during the development of the pipeline, is that the data infrastructure is of crucial importance.

The data infrastructure is organised in a way that enables the data to be usable for other applications. From a technical perspective, the 3D standards that are in development on both a national and international scale are closely monitored.[20] By organising and arranging the data infrastructure and file formats in this manner, the research data of 'Mapping the Via Appia' remain available and usable for numerous new 3D applications.

Discussion and conclusions

This article has presented the pipeline for the development of the 3D GIS for 'Mapping the Via Appia'. Based on a qualitative analysis of the user requirements, a data structure and implementation of tooling have been presented. The data structure of the server is fully operational. The data that will derive from the forthcoming fieldwork campaigns an easily be integrated into the pipeline. The OSG application is currently in a beta status, and will be tested and adjusted in close collaboration with the potential users.

The pipeline presented here gives the researchers of the 'Mapping the Via Appia' project the possibility to store their fieldwork data in a structured manner. Certain aspects of the pipeline have already proven to be valuable in the research master thesis by Rens de Hond. The data structure enabled him to easily select samples from the point clouds and meshes for his study of the reconstruction of the pyramidal funerary monument that stands along the sixth mile of the Via Appia, near the Villa of the Quintilii.[21]

The function that enables the querying of the research area, based on attribute values, in an innovative manner has not yet been tested systematically for their added value. The same goes for the function that enables the analysis of historic images by positioning them in and comparing them to the actual situation in the virtual 3D environment. Whether the 3D GIS contributes to a better or more efficient archaeological analysis, will be investigated systematically in the coming years, when the system will be in use. Important aspects here are the user comfort and the technical performance of the 3D GIS. Therefore, this article and the 3D GIS itself must be considered as the results of a first stage. The pipeline is an important methodological step in the development of 3D Geographic Information Systems in archaeological projects.

Valorisation

Although the 3D GIS is primarily intended as a tool for archaeological scientific analyses, it also provides possibilities to present the scientific results to the public in an innovative way. Since the data structure is organised in such a way that makes data exchangeable between various data formats, the data and future results might be integrated in augmented reality applications.[22] The research area can even be printed in 3D (fig. 6). 3D-printed models of reconstructions from different eras could be an asset for a museum exhibition.[23] Also, given the many developments in the field of 3D viewers, in the short term the possibility will arise to offer the data through a web interface.[24]

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Table 1. Overview of the user requirements (table authors).

User requirement	Data collection	Data structure	Tooling
Accurate measuring (maximum error of 5 cm)	Method for measuring within a 5 cm error		Implement tooling for measuring in the 3D environment
Querying archaeological sites and objects in 3D, based on attribute values	- Define sites and objects during fieldwork - Document features of sites	- Relational database - 3D objects that define sites and objects - IDs that enable link between database and 3D objects	- Define 3D objects - Relate 3D objects to relational database - Query database and visualise outcome in 3D application
Positioning historic images		Enrich images with 3D orientation and view point	Tooling for positioning images in 3D environment
Simultaneous access to data from multiple locations		Disseminate data structure via a server	The application needs to communicate with the servers
Integration of 2D GIS data		Apply GIS data standards for exchange of data	3D application must be able to read 2D data; work with exchangeable GIS standards
Import archaeological 3D reconstructions		- Upload generated 3D reconstructions - Export 3D measurements to 3D modelling software	Import and export functionalities for 3D data
Exchange of data with other information systems		- Apply geo and 3D data standards - Structured data	

Figure 1. The Via Appia on the sixth mile (photo Rens de Hond).

Figure 2. Point cloud measurement by Fugro's FRIVE-MAP application (figure authors).

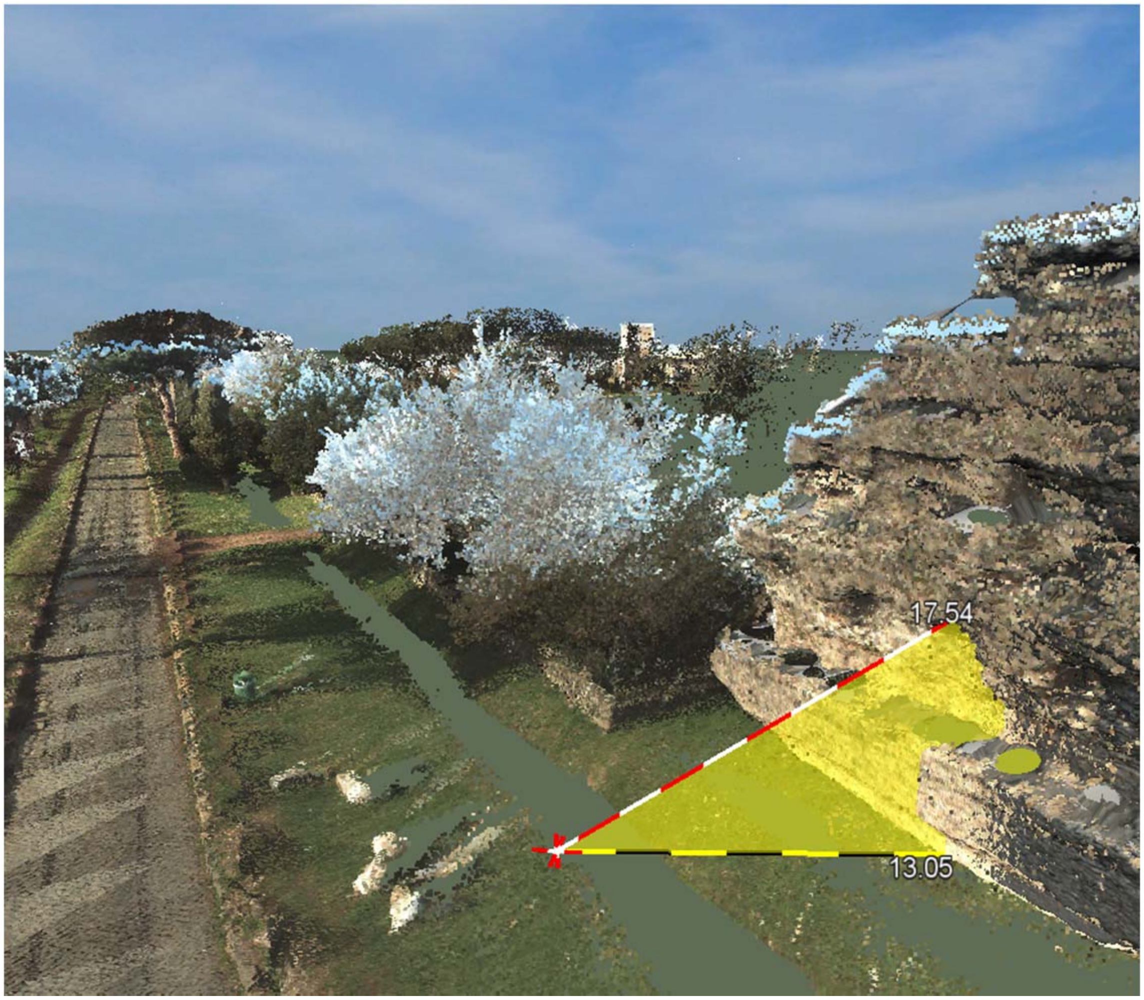

Figure 3. Measuring in the OSG application (figure authors).

Figure 4. Via Appia data in the OSG application (figure authors).

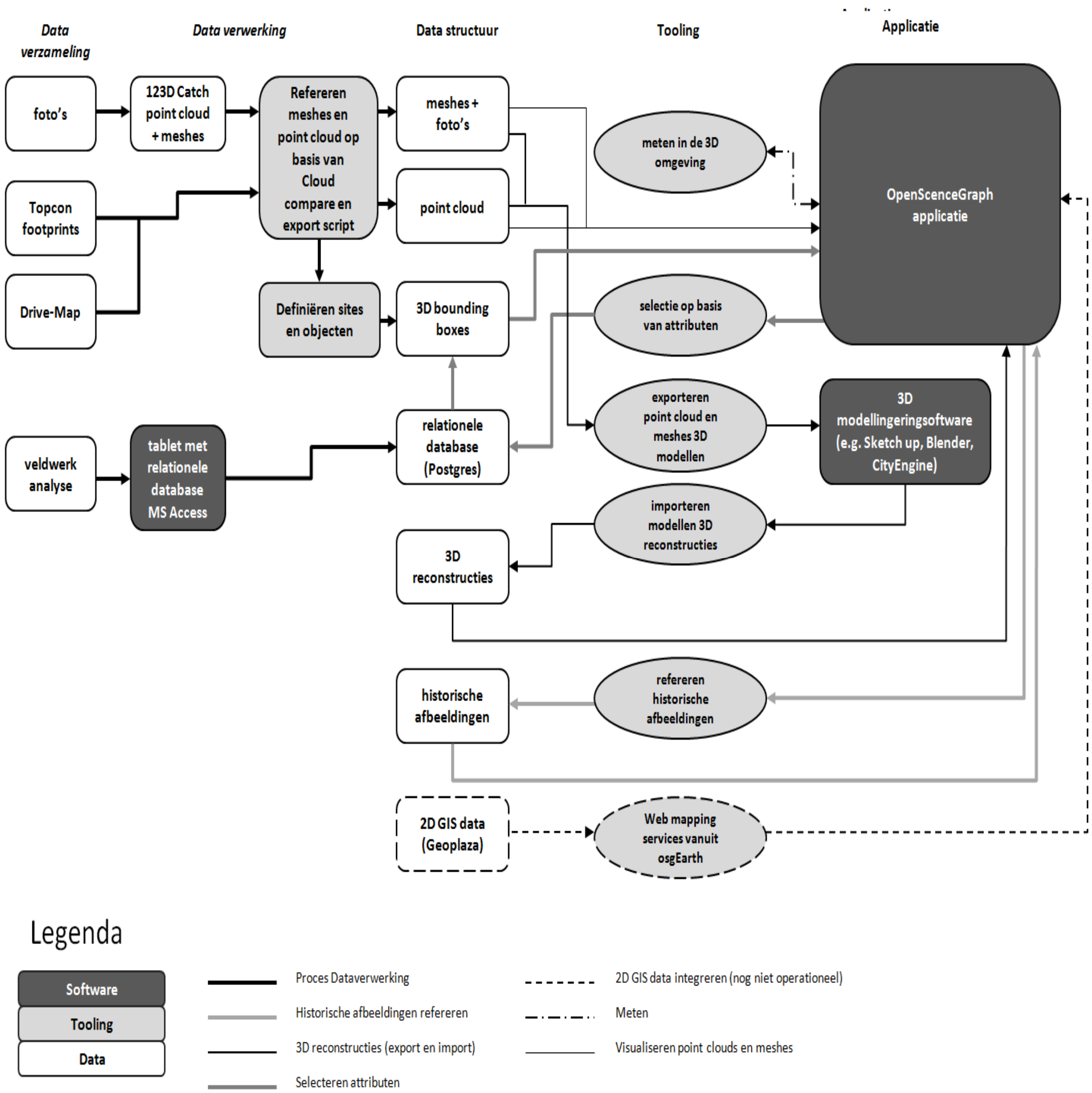

Figure 5. The pipeline for the 'Mapping the Via Appia' 3D GIS (in Dutch) (figure authors).

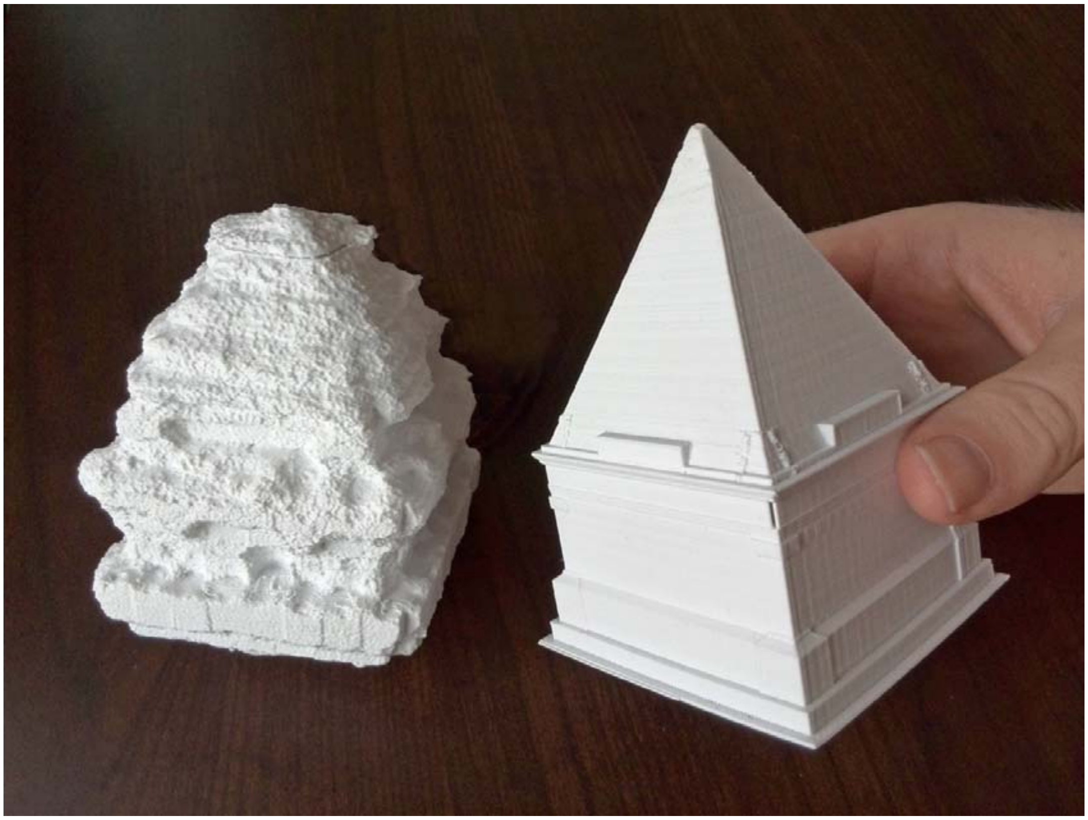

Figure 6. 3D prints of the research data and results (thanks to Alexander Hermanns - Indicia) (photo authors).

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[1] This article has been published in Dutch as De Kleijn, M., De Hond, R., Martinez Rubi, O. & Svetachov, P. 2014, 'Een 3D-Geografisch Informatiesysteem voor 'Mapping the Via Appia'', in: *Tijdschrift voor Mediterrane Archeologie*, 52, pp. 7-13. The authors express their gratitude to the editorial staff of *TMA* for their permission to publish this translation. Preliminary results of this research have previously been published in De Hond 2014a.

[2] See for instance Connoly and Lake 2006 for the added value of GIS for analysis. In many countries it is mandatory to deliver structured data. In Rome, Italy, this is according to the Sistema Informativo Territoriale Archeologico di Roma (SITAR). http://sitar.archeoroma.beniculturali.it/.

[3] 3D technologies are being applied in archaeology from the 1980s onwards: see Miller & Richards 1994. An indication for the recent growth of the number of 3D projects in archaeology is the fact that Computer Applications & Quantitative Methods in Archaeology (CAA) has dedicated complete sessions to 3D for some years: http://caa-international.org/. In a heritage context it is good to mention the V-MusT.NET Virtual Museum Transnational Network: http://www.v-must.net/. Many projects are focussed on 3D reconstructions and accurate measuring in 3D.

[4] 'Mapping the Via Appia' is a collaboration between Radboud University Nijmegen, VU University Amsterdam, Royal Netherlands Institute in Rome (KNIR), and the *Soprintendenza Speciale per i Beni Archeologici di Roma* (SSBAR). The project is funded by *De Nederlandse Organisatie voor Wetenschappelijk Onderzoek* (NWO) (project number 380-61-001) and the Netherlands eScience Center, http://esciencecenter.nl/ (file number 027.013.901). The development of the 3D GIS is led by the Spatial Information Laboratory (SPINlab) of the VU University, http://www.feweb.vu.nl/gis/home/, and conducted in collaboration with the Netherlands eScience Center and the Center for High Performance Computing and Visualisation of the Rijksuniversiteit Groningen, http://www.rug.nl/science-and-society/centre-for-information-technology/research/hpcv/?lang=en.

[5] Portella & Ventre 2004.

[6] Mols, Moormann & Pelgrom 2013.

[7] Such as SketchUp: http://www.sketchup.com/, Blender: http://www.blender.org/ or CityEngine: http://www.esri.com/software/cityengine.

[8] The differential GPS used in the 'Mapping the Via Appia' project is the TopCon HIPer Pro.

[9] The database used during fieldwork is set up for MS Access and is filled in directly in the field using a tablet.
[10] PostgreSQL is a powerful open source database: http://www.postgresql.org/.
[11] For more information on DRIVE-MAP, see http://www.fugro.nl/werkgebieden/geo-informatie/asset-informatie/data-inwinning/.
[12] To download 123D Catch, visit this website: http://www.123dapp.com/catch.
[13] 123D Catch is a closed service by Autodesk, which is a drawback. Autodesk offers the service for free, but does not openly provide information on their method. This means that there is no certainty concerning the accuracy of the photogrammetric analysis and the creation of the meshes.
[14] CloudCompare can be found here: http://www.danielgm.net/cc/.
[15] PostGIS is an extension for PostgreSQL, and enables various GIS analyses. For more information on PostGIS, see http://postgis.net/.
[16] For more information on OpenSceneGraph, see http://www.openscenegraph.org/.
[17] An expansion to OSG4WEB in a later stage would make a web application possible. OSG4WEB is still in development. See http://3d.cineca.it/storage/demo_vrome_ajax/osg4web_adv.html.
[18] Based on protocols initiated by the Open Geospatial Consortium (OGC), such as web mapping and web feature services (see http://www.opengeospatial.org for more information).
[19] Geoplaza is accessible at http://geoplaza.ubvu.vu.nl/cms. An extensive explanation of Geoplaza is given in De Kleijn, Kolen & Scholten 2014.
[20] For this purpose, the project members have joined the Special Interest Group 3D of the Dutch institute for Geostandards Geonovum: http://www.geonovum.nl/onderwerpen/3d-geo-informatie/special-interest-group-3d.
[21] De Hond 2014b.
[22] Nowadays, augmented reality applications are frequently used in archaeology. Using smartphones or Google Glass, visitors can see virtual 3D models positioned in the ‘real’ world.
[23] A first test of 3D printing one of the monuments has been executed, thanks to Alexander Hermanns from Indicia (http://www.indicia.nl/).
[24] Examples of current developments for 3D web interfaces are Unity 3D, http://unity3d.com/webplayer, and three.js, http://threejs.org/.

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