SCIRES it
SCIentific RESearch and Information Technology
Ricerca Scientifica e Tecnologie dell'Informazione
Vol 6, Issue 1 (2016), 23-30
e-ISSN 2239-4303, DOI 10.2423/i22394303v6n1p23

DIGITIZING INDOOR AND UNDERGROUND CULTURAL HERITAGE SITES WITH ROBOTS

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Abstract

In this paper we describe our novel approach for acquiring and managing digital models of archaeological sites, and how we plan to showcase it during the Digital Heritage Expo 2015. In particular, we will demonstrate three technologies: our robotic system for digitization of archaeological sites (DigiRo), our cloud-based archaeological information system (ARIS), and our immersive virtual reality app for virtually visiting the digitized sites (VR Tours).

Keywords

Digitization, Robotics, Virtual Tourism, Archaeological Data Management.

1. *Introduction*

Programmed conservation of cultural heritage sites is a complex strategy that requires the cooperation of several actors (i.e., surveyors and cultural heritage professionals) as well as inter- and multi-disciplinary approaches involving diagnosticians, restorers, art historians, chemists, architects, etc.

The main aim of this strategy is to replace the (more or less traumatic) restoration on a heritage site with a continuous process that involves knowledge, prevention, monitoring and planning of interventions. From this point of view, monitoring plays a key role: it allows to study and analyze the causes, the effects and the progression of the decay of a target heritage site. Data acquisition, processing and maintenance are crucial issues in monitoring: in a typical scenario, surveyors access the target heritage site with the needed sensors (e.g., laser range finders or cameras) to collect as much data as possible; this data is then processed in order to retrieve meaningful information for conservation (e.g., maps, 3D reconstructions, annotated images, etc.); finally, the huge amount of heterogeneous data has to be integrated and maintained through special data integration environments.

We believe that the procedure of data acquisition, processing and maintenance has space for improvements in terms of time (surveys and data processing may require a lot of time), human safety (some sites may be difficult or dangerous to access), reuse of models and information (3D reconstructions produced by the conservator could be fed into a digital archive of the site for further analysis and promotion).

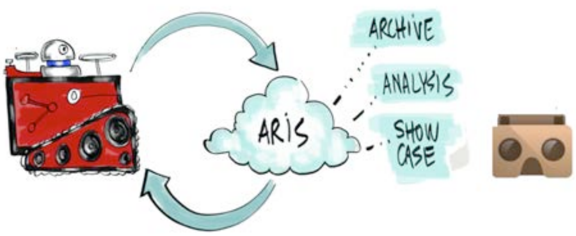


Fig. 1: The ROVINA concept

Fig. 2: Our robot digitizing the Catacombs of Priscilla

Our approach, has been developed within the ROVINA FP7 EU project[1], that involves the University of Bonn, the RWTH University of Aachen, the Katholieke Universiteit Leuven, the Sapienza University of Rome, Algorithmica S.r.l. and ICOMOS-IT. The project aims at making surveys of indoor or underground cultural heritage sites more efficient and safer, through the use of autonomous robots. At the same time, this approach addresses the problem of managing the huge amount of data produced by the robot, through a cloud-based information system. To evaluate the project progress, we selected catacombs as case of study: catacombs, indeed, are indoor sites very rich in both geometrical and texture features, such as loculi, chapels, tunnels, ramps, frescos and epigraphs.In the following, we will describe the three core components of the ROVINA digitization project for indoor sites (see Figure 1): the Digitalization Robot (**DigiRo**) which can explore many kinds of unknown indoor sites (autonomously or supervised), the Archaeological Information System (**ARIS**), that implements an easy-to-access cloud-based archive for all types of data collected during the surveys, and the immersive virtual reality app for virtually visiting the digitized sites (**VR Tours**).

2. *Robotics for Cultural Heritage: Innovation beyond the State of the Art*

There have been many attempts to use robots to explore hard-to-access sites (see Thrun et al., 2005), however, most of these systems are tele-operated or follow a predefined path and their goal is to get only a preliminary vision of unknown sites. DigiRo, on the other hand, is one of the first platforms for performing methodological surveys of unknown cultural heritage sites. We achieved this result thanks to an iterative design process of the robotic platform (currently at its third iteration) and to the integration and the development of novel algorithms that extend the current state of the art in autonomous mapping and localization, 3D reconstruction and on-line analysis.

In order to allow DigiRo to survey archaeological sites in an autonomous or semi-autonomous way, several challenges had to be addressed, and computer vision and robotics solutions have been developed. At the core of the platform intelligence there is the capability of simultaneously building a 3D map of the environment and localizing within this map (SLAM). We extended different so-far state-of-the-art components such as g2o (Kuemmerle, Grisetti, Strasdat, Konolige, & Burgard, 2011), DCS (Agarwal, Grisetti, Tipaldi, Spinello, Burgard, & Stachniss, 2014) and a variant of ICP (Serafin & Grisetti, 2015), thus developing a novel 3D reconstruction system. Compared to most existing reconstruction methods, our system builds models in real-time during operation: this is important in order to allow the robot to act autonomously and to allow for own decision-making based on the environment explored so far. We have devoted a considerable effort in making the approach more robust and developing an extension of DCS, originally proposed by Agarwal et al. (2014), to assessing the degree of consistency of maps (Mazuran, Tipaldi, Spinello, Burgard, & Stachniss, 2014) and to automatically calibrating the sensors (see also Basso, Pretto, & Menegatti, 2014). In order to safely navigate in

[1] http://rovina-project.eu

the environment, the robot uses an abstract 2D representation of the environment called traversability map (Bogoslavskyi, 2013) that, when coupled with exploration techniques that consider the expected gain of novel information (see Stachniss & Burgard, 2014, for an overview tutorial), allows for a safe and exhaustive survey of the environment.

Despite being still a research prototype, our robot has already obtained a number of achievements, showing that it has a good mobility and that it can run for a long time while processing huge amounts of data from a number of heterogeneous sensors. During the survey, while collecting data for off-line processing, the robot builds an on-the-fly mission-oriented reconstruction of the surrounding environment, that can be used either by the autonomous navigation system, or by a human operator through a mission control interface. DigiRo has already accomplished a number of successful missions and its results have been presented at the Maker Faire European Edition 2015 where it won the Maker of Merit award.

The robot has the capability of acquiring huge amounts of data that needs to be reconstructed into meaningful and high level models, such as 3D reconstructions or semantic classes, in order to support cultural heritage professionals in their conservation activities. The amount of data and the complexity of the reconstruction process is such that it cannot be efficiently handled by a single computer. For this reason, the data collected by the robot is uploaded to the cloud where ARIS, our information management system, processes it in order to offer a number of different services. Although there are already many interesting examples of archaeological information systems (e.g., the Arches Project[2] by the Getty Institute), these projects focus on descriptive artifacts where qualitative data, such as textual descriptions, is manually provided by human operators. On the contrary, our information system is focused on the management and automatic interpretation of large amounts of quantitative raw sensor data, such as laser scans, 3D images and pictures. To this end, ARIS is capable of automatically generating accurate 3D models and to automatically classify data into semantic classes through the use of beyond state of the art Artificial Intelligence technologies.

Indeed, 3D scans and images can be interpreted more effectively within aggregate 3D models than on their own. In ARIS we compute 3D reconstructions of two different types: 3D point clouds and textured 3D meshes. For example, Figure 3 shows a small portion of a textured 3D meshed reconstruction of a catacomb that ARIS has computed from high-definition photos by using state-of-the-art photogrammetry approaches (Vergauwen & Van Gool, 2006; Theo Moons & Vergauwen, 2008). ARIS allows to export user-defined portions of the textured 3D meshed models into a mobile app, called VR Tours, that, when coupled with virtual reality visors, can provide a powerful mean for dissemination and promotion of cultural heritage sites. The VR Tours app can be published on existing app stores, thus becoming also a potential source of income for site owners. Moreover, ARIS automatically annotates both 3D models and raw images according to user-defined taxonomies and ontologies, in order to provide advanced search and analysis services. The automatic semantic annotation of data in ARIS relies on a novel machine learning approach (Hermans, Floros, & Leibe, 2014), that combines Random-Forest-based classification with Conditional Random Fields that has won the IEEE ICRA'14 Best Vision Paper Award.

Fig. 3: Example of image based reconstruction, using high-definition camera pictures

3. *Demonstration at the Digital Heritage Expo 2015*

In this section we will describe the installation and the demonstrations that has been carried out in the Digital Heritage Expo 2015. Our goal was to show to the visitors, in an engaging and fun way, how easy it is to use our system to improve

2 http://archesproject.org

monitoring of cultural heritage sites. To this end, we have provided a user perspective to the system rather than a technical one, where users have been challenged to try to use the system themselves. In particular, we asked visitors to be surveyors, and thus use the robot to explore and reconstruct the surroundings of the booth using the mission control interface. We then asked them to act as cultural heritage professionals and use the web based interface to ARIS to explore the data we have collected during the many missions in the catacombs of Rome. We finally asked them to be virtual tourists and explore though our virtual reality headset ARIS's reconstructions of the Catacombs of Priscilla in Rome, using the VR Tours app.

3.1 Robot surveying with DigiRo

The first part of our demonstration consisted in the usage of the DigiRo robot (see Figure 2). The robot is composed of a tracked mobile base equipped with a custom IP67 case that has been designed to properly house the sensors and the computational units, while being resistant to environmental challenges such as high humidity, dripping water and dust. The sensor suite, which can be customized by design for specific survey missions, includes a 3D laser range finder and three RGB-D cameras, as well as temperature and humidity sensors and sensors robot status such as an inertial measurement unit and a battery status monitor. The prototype will also include a number of computational devices that composes a distributed system with plenty of computational power: it has two laptops and six single-board computers that communicate through a high-performance Gigabit Ethernet within the robot. Visitors inspected the robot internals, sensors, computational devices, while we provided explanations about the working principles and showed how the platform can be customized with different sensors. We also presented concept designs of our next generation of robots that will allow to extend the range of environments that can be automatically surveyed, including churches, palaces, castles and underground environments that have greater mobility and sensing challenges.

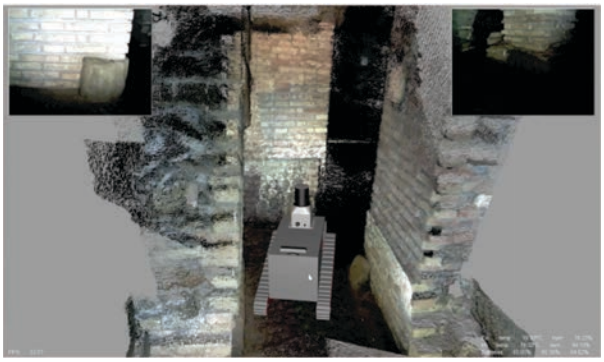


Fig. 4: The Mission Control Interface, showing a point-cloud-based on-line reconstruction.

We showed videos about DigiRo performing missions in catacombs, through the MCI interface[3], showing the mission experience from the point of view of a surveyor, while the robot explores the Catacombs of Priscilla in Rome, that is our main case study. Finally, we performed live demonstrations of an indoor environment digitization, at the installation booth. During these demonstrations, we allowed visitors to operate the robot through the Mission Control Interface (MCI) and perform the survey of the surroundings of the booth. The MCI shows in real-time the 3D reconstructions (see Figure 4) as the visitor moves the robot and allows the user to enable several levels of autonomy, ranging from tele-operation to semi-autonomous exploration.

3.2 The Archaeological Information System

The second part of the demonstration addressed ARIS, our cloud-based archive for the management and analysis of data collected by the robot. More specifically, we allowed users to access the cloud-archive of data collected by our robot in the Catacombs of Rome through the ARIS web interface and to experience the documentation, archival and classification services therein offered[4].

ARIS is a collaborative platform that allows for users with different types of expertise to cooperate in analyzing and processing the data acquired by the robot. A dashboard provides an overview at a glance of the state of the archive plotting statistics on the data, the activities and the load of the system (Figure 5b). In addition it

3 See video at http://youtu.be/l6MKMsnyHJw
4 See video at https://youtu.be/o2CHMbFLIi4

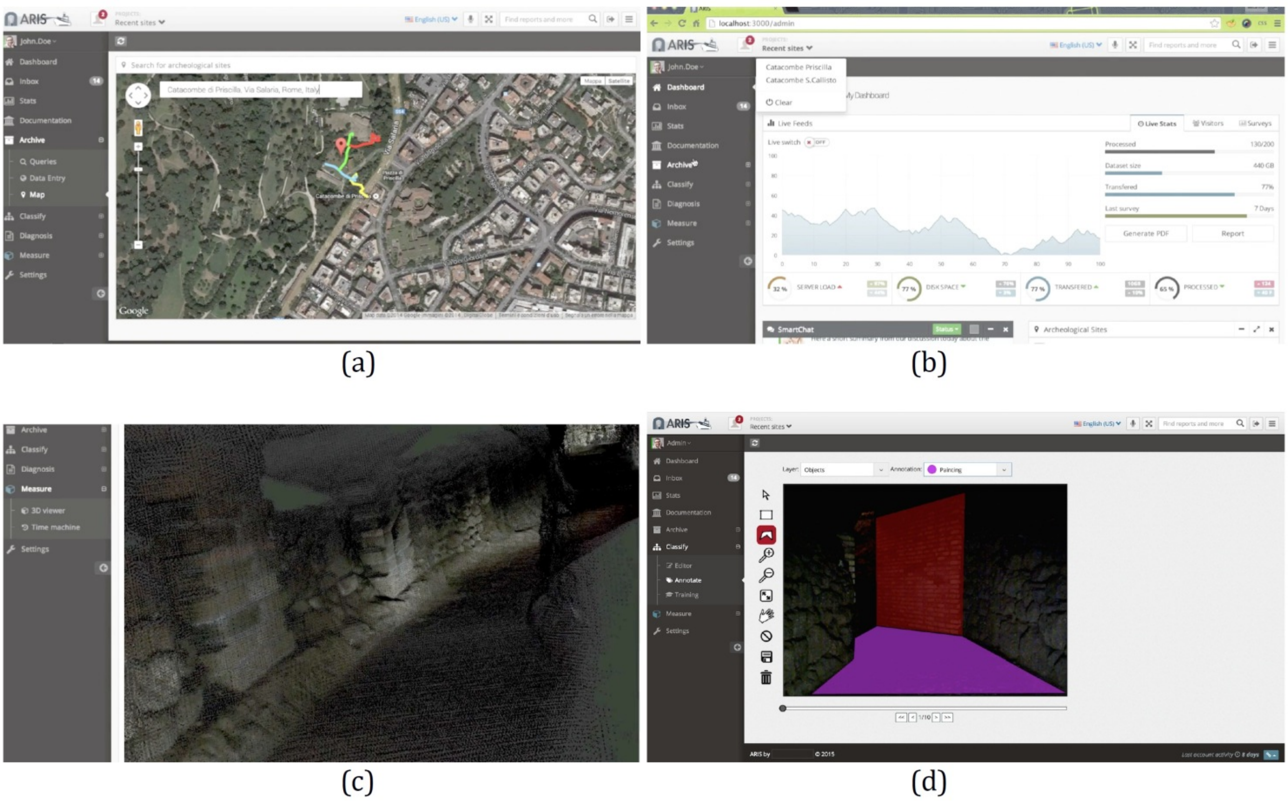
provides collaborative tools such as shared calendars, task lists, messaging boards and chats.

A core functionality of ARIS is its data archive. Data is organized in sites, such as the Catacombs of Priscilla or the Catacombs of San Gennaro. Each site is a collection of datasets, each of which contains the data collected during a single survey. The archive's interface allows to upload and to post-process data in several ways. For example, one can process it to build 3D point clouds or meshed maps, or classify it automatically or prepare it for visualization. Processing is performed as a background task and takes advantage of the computational structure of the cloud infrastructure.

Once the data is processed, it is made available to users in two different ways. Datasets can be queried though a GIS interface that presents the results as overlays over Google Maps. For example, if one searches Catacombs of Priscilla (see Figure 5a) the system will focus on the location of that particular catacomb showing the datasets as colored poly-lines that users can click in specific locations to access data that is localized there. Another way of accessing data is through the semantic queries. Users can specify a query as a conjunction of criteria across a number of user-defined semantic layers. For example, one could look for all the epigraphs (objects layer), which are in the region of Lazio (geographic layer), which are made of marble (materials layer), and which are from the II Century (historical layer). The system will then return all the datasets that contain items that correspond to those criteria, providing links to the images and locations in the 3D models where those items appear.

Semantic queries are possible thanks to the automated classification mechanisms offered by ARIS. As mentioned above, users can specify custom layers and within these layers custom classes. ARIS offers a specific interface to define such taxonomies and to associate classes to user defined colors. In addition to that, there is an HTML5 interface (see Figure 5d) that allows to annotate images by highlighting parts of the image based on their class. Users can annotate a small number of images that can then be given as examples to ARIS's Machine Learning technologies that will learn from those example and then automatically annotate all the other images and the 3D models.

As mentioned above, the data collected by the robot can be processed in order to build consistent and accurate 3D models that can be either colored point clouds or textured meshes.



(a) (b) (c) (d)

Fig.5 ARIS web interface

ARIS provides specific WebGL viewers (see Figure 5c) to have high fidelity 3D visualizations of these models directly in the browser. The 3D viewers allow for a number of different services, including measurement activities.

3.3 VR Tours

The third part of our demonstration allowed visitors to explore the 3D reconstructions of the Catacombs of Priscilla made by our robot, through our virtual reality app VR Tours. In fact, the textured 3D mesh models generated in the context of our project are both accurate and visually appealing and can be used for promoting the site to the general public. In particular, within the ARIS interface we allow to export custom paths within the sites for tourists to virtually visit high-quality 3D textured reconstructions. These reconstructions are made interactive thanks to the semantic annotations and to additional informative media (e.g., videos, text etc.).

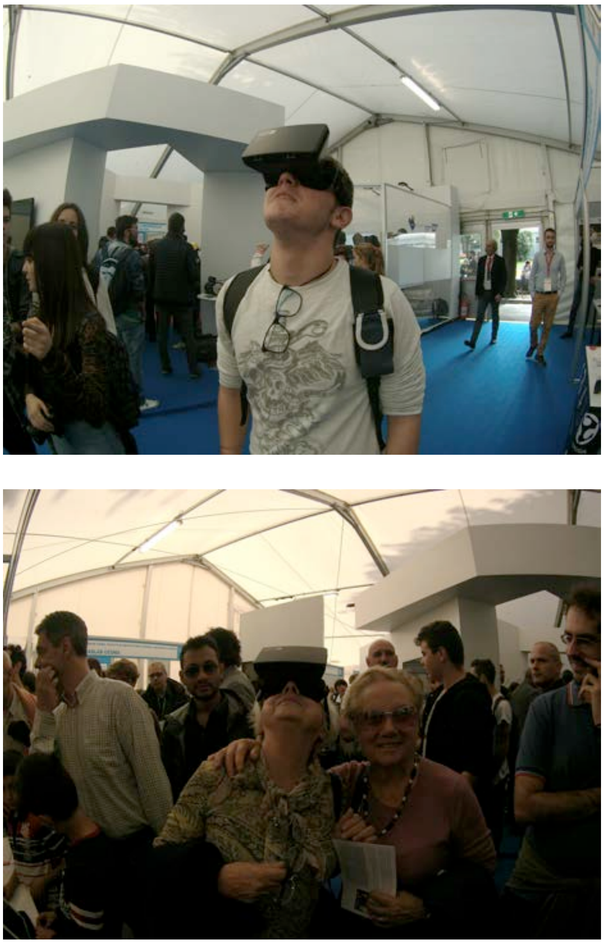


Fig. 6: People using the VR Tours app

In our installations, visitors have been able to virtually explore the sites, by the means of the VR Tours mobile app where they were able to enjoy these guided tours, walking through the predefined paths, stopping at will and looking around by moving the mobile device as if it were a window into the virtual world. These virtual tours are 3D and fully immersive thanks to the use of VR kits such as the Google Cardboard or similar (Figure 6).

4. Conclusions

This paper presented a novel, robot-based digitization system, called DigiRo, that is coupled with an archaeological information system called ARIS. We have designed, developed, and implemented the whole pipeline, during the ROVINA FP7 EU project, starting with a digitization robot with autonomous capabilities and a state-of-the-art 3D reconstruction systems.

Once the data acquisition has been completed, data are stored in a novel, user-friendly Archaeological Information System that we developed. It targets on easy access to all types of data collected, including similarity queries, machine learning approaches, and semantic search. In this way, our system simplifies and partially automates the surveying process of cultural heritage sites.

Despite being at an early stage, we already achieved a number of important goals. Three prototypes of the robot have been developed and are currently being used to record data. The obtained datasets show that our 3D reconstruction and semantic segmentation algorithms are capable of generating small-scale models that have many of the features of the final system.

We also developed the storage and interface system to allow easy access to the digitization results. Currently, we are improving and integrating our developed techniques, while exploring new challenges related to autonomous navigation, improving the user interfaces and making the user experience in VR Tours more attractive and immersive.

The full system has been presented during the Digital Heritage Expo 2015 (Calisi, Giannone, Ventura, Salonia, Cottefoglie, & Ziparo, 2015), earning many positive feedback from visitors, especially regarding the final results of the reconstruction process that is visible through the VR kits.

Our system also received two awards at the Digital Heritage Expo 2015: the Technical Proficiency Award and the People Choice Award.

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