Digital Archaeology Field Recording in the 4th Dimension: ArchField C++ a 4D GIS for Digital Field Work

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***Abstract* With the rapid adoption of laser scanning and photogrammetry among the archaeological community the creation of point cloud 'data scaffolds' and digital documentation of archaeological sites is now becoming common. In field excavations, however, the continual exposure of archaeological layers requires a digital toolset in which to record, categorize and spatially locate artifacts, installations, and loci within a site's daily 3D or aerial scan. We present ArchField C++, the latest version of our digital field recording software that enables real-time digital GIS 3D Top Plan production within a rendering engine designed for visualizing massive 3D datasets. ArchField directly connects to Total Stations and our RTK GPS units to record sub-centimeter measurements for artifacts, scanning markers, loci boundaries, and camera positions. The processing pipeline enables the generation of publishable orthographic and perspective maps from the first day of excavation to the last. As a backend it uses a PostGIS database and the ability to export and import various vector, raster, DEM and 3D datasets that can be hosted by on-line geo-referenced databases. We present the application of ArchField C++ to our 2014 field excavations of the early Iron Age site of Khirbat al-Jariyah located in Southern Jordan.**

***Index Terms*—Archaeology, cultural heritage, scientific visualization, structure-from-motion, LiDAR, geographic information systems (GIS), Level-of-Detail, Digital field recording**

I. INTRODUCTION

Over the past decade, digital archaeology field recording has become commonplace and cost effective with the integration of digital surveying equipment (Total Stations and RTK GPS), low cost tablets, and especially photogrammetric software. The question now is how do these instruments become integrated within the archaeologists' core toolbox to handle what will become an overload of daily scans, recordings, and digital documentation. In 2014, at Khirbat al-Jariyah, Southern Jordan, the excavation methodology was fundamentally changed when daily aerial and terrestrial SfM (Structure-from-Motion) was introduced. The result was massive 3D datasets of point clouds, textured meshes, and gigapixel resolution orthophotos that could not be easily rendered simultaneously and over different days of excavation by any off-the-shelf software. In addition, in order for this daily deluge of data acquisition [18] to be ideally used in the field it would need to render a digital Top Plan that contained not only vector artifact positions and loci but multiple layers of massive point clouds and 3D meshes. In response, ArchField C++ was developed to address these problems. It is the latest evolution of an integrated field recording software that has been developed over the past five years in coordination with ongoing field excavations. ArchField provides a unified software to combine high precision spatial recordings (survey and LiDAR/SfM) with supervisor's observations and digital spreadsheets. Integrated databases are seamlessly synced between the field excavations and lab analyses to enable raw data from the field to be immediately visualized as 4D top plans and queryable field reports in real-time.

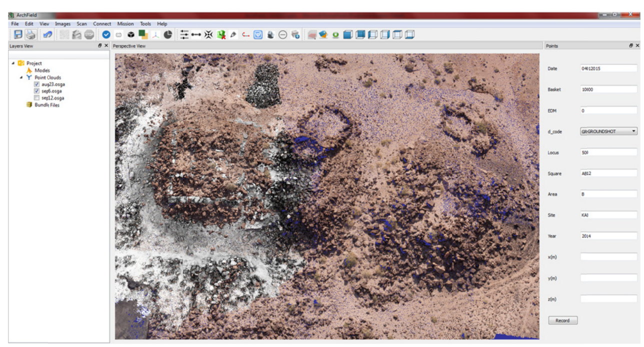

Fig. 1. ArchField C++ main gui showing Khirbat al-Jariyah (KAJ) excavation datasets.

This research and writing was funded in part by NSF IGERT and King Abdullah University of Science and Technology.

978-1-5090-0048-7/15/$31.00 ©2015 IEEE

Fig. 2. Aerial Map of Southern Edom research area, depicting the sharp elevation change between the lowlands and highlands of Ancient Iron Age Edom. Sites excavated or sounded by the ELRAP/L2HE projects (Map data: Google, Digital Globe 2012, LandSat7)

In this paper, the fundamental challenges in digital field recording in the 4^{th} dimension (time sequences in the excavation) and current solutions integrated into ArchField C++ are addressed. The software is a 4D GIS tailored for archaeological field work (fig. 1). Its major contributions to the field of scientific field recording include:

- Time-lapsed viewing of massive 3D point clouds, textured meshes and orthophotos.
- An intuitive interface for user editing, drawing and annotation of 3D datasets
- Multi-DBMS Integration: SQL + NOSQL

ArchField C++ represents a novel breakthrough in 4D digital recording and visualization that can be immediately applied and integrated into any archaeological excavation currently carried out in various regions throughout the world.

II. Literature Review

3D/4D GIS software for archaeology has been an ongoing topic of research and development for the past three decades. Perhaps the first implementation of a tailored GIS for archaeologists is DATARCH [5], an image management system where different media, primarily digital photos, could be stored and connected to a relational database. ArchaeoloGIS [17] and ETANA-GIS [9] were designed as open-source GIS map servers that could take basemaps (generated in ArcGIS© from traditional excavation techniques) and database tables (recorded in Access© or other spreadsheet programs) and serve them on online. The one software specifically developed for archaeological field acquisition is REVEAL, an NSF funded computer vision project [8]. This is a recording tool that combines plan reports with continuous video recording of excavations and multi-view camera captures of important artifacts and features. The future goal of the project is to orient surfaces and artifacts in 3D space using techniques such as multi-view stereo.

In contrast to these in house software developments, many projects have adopted off-the-shelf proprietary GIS software (e.g. ArcGIS) or open source GIS programs (e.g. MapInfo, GRASS, OSSIM, QGIS) to digitize their data and publish studies in scholarly journals or in online databases [12], [20], [11].

Others have focused primarily on integrating surveying tools with LiDAR or SfM (e.g. [12], [2], [6], [7], [19]) to document excavations but do not integrate the results in a 3D GIS.

Several recent publications have attempted to integrate large datasets in a 3D GIS environment. In 2010, [10] developed a VR-GIS that optimizes the visual rendering of high poly count geometric models in a 3D archaeological environment. Their system supports path animation of the camera for fly-throughs and skeletal animation. Objects loaded into the scene can be manipulated or selected to access associated metadata.

Recently, work by [4] used Esri's ArcScene as a tool to manage a 3D GIS that includes textured models, artifacts, loci and other GIS related datasets. A significant advantage of this approach is that all the analytical and editing tools of ArcScene can be immediately applied to the archaeological datasets once properly imported. A major drawback is the limited rendering capability of ArcScene requiring the authors to simplify both the models and textures imported into the software.

MayaArch3D utilizes WebGL and directly links to a PostGIS server [1][3]. This program can handle limited Level-of-Detail (LOD) models in its navigable viewer and handles higher resolution models by effectively opening independent viewing windows. A major advantage of this software is that it can stream large content over the internet to many users.

In contrast to all of these projects, ArchField remains one of the few archaeological field recording tool with ongoing development and a full GIS DBMS. It is the only tool designed for archaeologists that does real-time recording with digital instruments utilized in field excavations. With ArchField C++ one more evolutionary step beyond its previous versions has been made by making 4D field recording and visualization possible.

III. A 4D GIS FOR FIELD RECORDING

In recent years, a number of conference topics have addressed the idea of a 4D GIS (c.f. DHIC 2013 and CAA 2015 abstracts). In certain respects, every digital excavation is four-dimensional and once imported into current 3D GIS tools such as ArcScene it can be considered a 4D GIS (e.g. [4]). However, these current solutions do not fully address the underlying problem: archaeology is an inherently destructive science necessitating continual advancement in field recording tools that achieve an increasing improvement in accuracy and comprehensive recording. 4-dimensional GIS field recording should be envisioned as the new objective in digital archaeology requiring a fundamental change in both methodology and software. In this light, four core objectives of a 4-dimensional field recording methodology can be proposed that will require an ushering in of a new era of digital field recording. The purpose is to address more fully the endeavor by archaeologists to conduct scientifically based excavations that properly examine all available archaeological evidence to test anthropological and historical theories about past culture.

Objective 1: 3D Scanning on a daily/hourly basis

A core objective is digital 3D scanning of the current excavation on a daily basis. Each day's 3D scan captures the newly exposed layers so that over the entire period of excavation every sedimentary change is documented. On an hourly basis as a new artifact, installation or even collapsed wall is discovered in situ, it's excavation and eventual removal is fully documented with 3D scanning. This can be accomplished using TOF (Time-of-flight) Laser scanning, but photogrammetry may prove the most efficient approach. Using the widely adopted photogrammetry software amongst the archaeological community, an entire and complete (minimal occlusion) excavation can be captured in minutes either from the ground or air [23]. The new problem becomes how to store, manage, co-register, and visualize such massive datasets being generated on a daily or hourly basis.

Objective 2: Integration of 3D layers with a spatial DBMS (Digital Database Management System)

In order to qualify as a 4D GIS, the 3D data must be integrated spatially with all other time-sensitive database entries. This would include other 3D measurements (e.g. GPS or Total Station), digital images, field databases, field notes, and later auxiliary tables generated from specialist analyses of artifacts, loci, stratigraphy or architecture. This integration would require 3D layers to be able to represent three different types of time:

1. Field Excavation Processes: The ability to represent the artifacts, loci, architecture, sedimentary layers exposed on a specific day of excavation (e.g. a 3D Top Plan).
2. Stratigraphy/Phasing: Represent an entire stratigraphic layer of a specific time of occupation by the original inhabitants. This would require the ability to represent the key 3D scanned architectural elements associated with only that period of occupation.
3. Site Abandonment and Deposition: Model the depositional layers produced through natural and man-made post-abandonment processes. This could include modeling a series of collapsed walls, how upper-stories overlay lower floors, the decay of organic materials, and even the movement/levitation of artifacts through erosional processes.

Objective 3: Real-time Visualization of 4D Top Plans

In the field, archaeologists should be able to visualize top plans as they are recorded with the ability to traverse in time how it looked in 3D during previous days. They should be able to visualize the data in its full resolution (no simplification or loss of fidelity) with viewable frame rates (min 24fps). This will require more efficient rendering systems that can run on a modern laptop in the field. Second, it requires more efficient algorithms for processing photogrammetry, syncing 3D scans, images, and other 3D recorded measurements. The software should be able to integrate seamlessly the data as it becomes available and dynamically update the top plans accordingly.

Objective 4: Analytical Tools tailored for 4D Data

Analyzing and manipulating data in a 4D environment will necessitate novel tools to facilitate annotation, editing, drawing, segmentation, and time-sensitive comparisons. In the remainder of this paper we present the current contributions to this new field with ArchField C++ software and how our field methodology has changed to account for this new approach. We present the results, challenges, and future directions.

IV. EVOLUTIONARY ADVANCES: ARCHFIELD C++

The development of ArchField has been an evolutionary process since 2009, undergoing five excavation seasons of modification and adaption to meet new demands in multifaceted digital field excavations. Previous versions were designed to run as imbedded web applications interoperable with many GIS software tools and even deployable on handheld tablets and phones [22]. However, there were a number of drawbacks to this approach primarily related to the limitations of being locked inside a web browser, limited memory allocation, slow rendering speed, restrictions on access and control, and complicated installation of the web server system or iOS app. Until the introduction of the Microsoft Surface, tablets and handheld devices that appeared as optimal field devices could not run x86 or x64 operating systems limiting the options and full advantages of such devices compared to a fully functional OS.

By the time of the last field season in September 2014, it was recognized that the growing philosophy of archaeologists to move everything digital to the web, online and on an iPad had significant drawbacks especially for field recording. In order to embrace a new philosophy of 4D field recording that would result in a deluge of massive datasets, ArchField would have to be rewritten as compiled C++ software that can take advantage of the full horsepower of modern computers and employ a sufficient 3D rendering engine. The biggest advantage in moving to a compiled C++ version is that an all-in-one solution with a no-hassle installation could be deployed on any Linux, Mac or Windows based rugged laptop or tablet. It runs much smoother on x64 based tablets, supports larger hard disks, more RAM, more powerful video cards, USB devices, serial communication, full local installation of any DBMS and, most important, a very fast 3D rendering engine can now support the new 3D content generated in the field.

ArchField C++ is built using QT5 similar to QGIS, Meshlab, Pix4D, Agisoft, Photoscan and many other tools that have become common-place software among the archaeological community. QT allows ArchField to be compiled for Linux, Mac, and Windows. Integrated as a 3D window in ArchField is OpenSceneGraph (OSG): a powerful graphics engine built on top of OpenGL (see for further detail [21]). It has already been used to build OSGEarth and QGIS has a plugin for its file formats. The other advantages include that it handles LOD rendering and specifically has tools already integrated for loading a variety of 3D file formats. All the previous work for visualizing vector data and communicating with PostGIS could be ported over from ArtifactVis2. All the current features of ArchField could also be easily coded much faster in a much more versatile object oriented programming language such as total station serial communication, project tailored setup, barcode label generation, intelligent artifact/loci data entry, top plan symbology generation, etc. (see [22]).

ArchField C++ is designed to have the feel and versatility of QGIS but tailored to archeologists needing a 3D rather than planar 2D GIS. This includes tools for view manipulation, bookmarking, and manageable layers that can be turned on and off with symbology. It maintains interface with Total Stations but is now fully integrated so that ArchField directly opens the serial connection and handles processing of incoming results. Data can be recorded as in previous version of ArchField but now with dockable windows.

In figure 1, the main application gui can be seen. It renders two massive point cloud datasets (>10M each) simultaneously allowing the user to toggle between time-lapsed based 3D reconstructions of the KAJ excavations. The left dockable window pane functions similar to other GIS software where multiple diverse spatial layers can be loaded and toggled on and off. The main difference is that now full 3D models can just as easily be loaded in conjunction with traditional GIS datasets (points, polygons, raster images) without any delay in loading or rendering. The right dockable window depicts the recording system that directly stores user input and Total Station readings inside a PostGIS database and adds the spatial information to the layers window. The upper toolbar contains various toggle tools for manipulating the 3D objects including, editing, selecting, and annotation. In sum, all of these features provide significant evolutionary advances.

V. Field Application: 4D Recording Methodology in Jordan-- Initial Results

In September 2014, a 4D digital field recording methodology was implemented at Khirbat al-Jariyah (KAJ), an Iron Age II copper production site in Southern Jordan (fig. 2). Since ArchField C++ was still being developed, ArchField Web version was used for recording all standard datasets as in the past but the field recording methodology was significantly altered to achieve objective 1: 3d scanning on a daily and even hourly basis. Every morning after sunrise, aerial images for SfM reconstruction were collected and then suplemented with terrestrial SfM reconstructions that captured pertinent features and loci that would change before the next morning. Several different open source and proprietary photogrammetry softwares were used to achieve optimal results.

The aerial SfM reconstruction was achieved by the use of a helium balloon mounted with a Canon EOS 50D and 18mm lens automatically triggered and angled at nadir (fig 3). Low altitude scanning using an aerial balloon with photogrammetric software had proved successful on numerous occasions and demonstrated in several previous projects [21].

Fig. 3. The low altitude aerial balloon used for daily aerial SfM reconstructions. The balloon was inflated full during the entire season requiring only taping off every week the helium.

In comparison to the UAV quad copter, the balloon required less maintenance and most important perfomed well irrespective of windy conditions, a common experience at KAJ. The balloon proved an efficient method to regularly scan the site. The GPS dependent flight missions of the quadcopter were replaced by a tethered balloon with a human simply walking the site in a lawnmower pattern (fig 4). The low altitude balloon was found to be a viable, cost effective solution, and facilitated the capture of high resolution imagery given the baloon’s ability to carry a full DSLR camera.

A grid of ground control points were marked throughout the site and measured using ArchField connected to a Total Station. These GCPs (GCP = Ground Control Point) were used in the SfM softwares to properly register each day’s reconstruction.

In order to achieve optimal resolution and coverage, multiple passes of the excavation area were taken by the baloon at different elevations. However, due to the configuration of the camera frame, the camera could not be angled to adapt to the exposed walls in the latter part of the excavation which would require not only nadir but also oblique images. In general, though, the reconstructions were not adversly affected by either of this drawback and produced sufficient results.

Fig. 4. A typical single image captured from the low altitude aerial balloon. Note the staff member is typically caught within the frame of the camera, at lower elevations, but is rarely reconstructed due to his changing movement.

In addition to the aerial scanning, at the opening/closing of every locus, a terrestrial SfM scan was taken (N = 100 loci). Terrestrial SfM scans were also acquired for significantly important in-situ artifacts and after every professionaly prepared photograph. For example, after an area was cleaned and swept for a professional photograph, the photographer would also take a series of overlapping pictures with multiple angles and attempt if possible to capture parts of the surrounding architecture that would have been captured by the aerial reconstructions or several of the near-bye GCPs. In order to organize the images and eventual reconstruction spatially in the database, a measurement was also taken by ArchField. Eventually, the goal would be to automatically match these terrestrial images to the already oriented aerial images rather than relying on the few available GCPs.

At the end of the 2014 field season, 121 sets of SfM models were collected over 21 days of excavation. The total size was 384GB (unprocessed) and 10,184 images. There were 21 aerial scans and 100 terrestrial scans with an average of 6 SfM sets generated per day.

There were a number of challenges faced with this change in recording methodology. First the excavation incurred a massive processing backlog for the SfM sets. The staff could only process 1-2 models a day due to the limited number of powerful workstations in the lab and the additional problem of itermittent power outages. Second, geo-referencing the SfM aerial sets became a non-trivial exercise as the excavation progressed. The area chosen for excavation is a complex monumental building completely covered in collapsed stone from tall walls. Many of the GCPs had to be removed or were bumped during the excavation of the building reducing by the end of the season the number of GCPs to 3 and in many cases it was more ideal to use unique features of the stones themselves for referencing one model to another. Even with detectable GCPs, significant time was spent for each set to locate the markers in the images irrespective of the different SfM software used. Over the season of excavation the weather and lighting changed. The coloring became inconsistent between different days of excavation. The poor lighting on certain days also led to lower quality images with a higher frequency of blury images or noisy images from a higher ISO setting. However, the greatest challenge of all was that there was no adequate software in which more than one day's 3D model could be visualized at a time. This prevented a comparison of the results and top plans lagged behind in what they displayed as the staff labored away to process the aerial orthophotos and rock drawings.

Although the switch to a comprehensive 4D recording of the site led to unprecendented digital data capture at a level of detail rarely captured on any excavation, it was clear that the dataset generated could not even be used to its full potential with any currently available GIS or 3D rendering software let alone viewed on a single laptop in the field by site supervisors where it would have been needed most. It is these challenges and the current lack of sufficient 3D rendering software for viewing 4D SfM sets that motivated and helped direct the development of ArchField C++ since 2014 until present.

VI. Real 4D Field Recordings Problems & Their Solutions

Beyond porting the current features of ArchField to a more efficient programming language, a major contribution of this current paper is the latest implementations developed for ArchField C++ that address the inherent problems detailed in the objectives of four-dimensional field recording and witnessed during the 2014 field excavations at Khirbat al-Jariyah. The field excavation dataset proved invaluable, since it provided a massive set of SfM reconstructions representing a daily time-lapse of the excavations that could be registered to all the vector based artifacts, loci, and PostGIS tables recorded by ArchField. The visualization of these digital maps can guide and orient the study of the day by day development of the investigations and/or changes of excavation strategies. Using this dataset several of the major challenges could be directly addressed providing a clear gauge of the current progress and future direction of ArchField C++. In this section, we highlight several of the novel solutions achieved through the development of ArchField C++ since the 2014 field excavations.

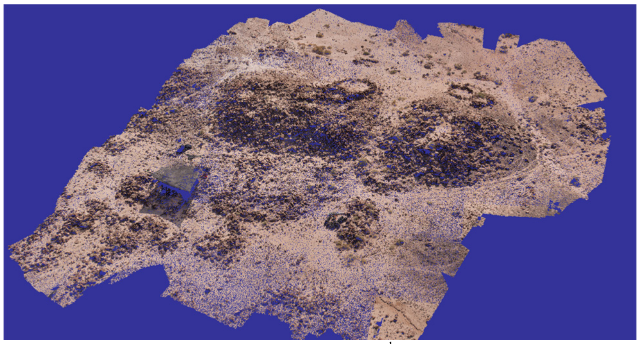

Fig. 5. The excavation area on August 23rd, 2014, as a 3D pointcloud reconstruction using BSP running inside ArchField C++.

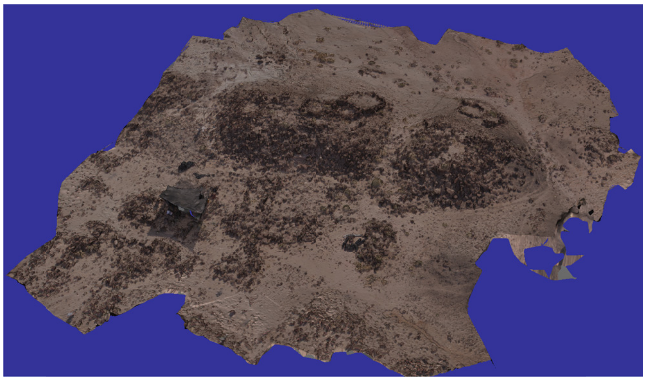

Fig. 6. The same August 23rd 3D reconstruction as a textured mesh using a quad-tree LOD running inside ArchField C++.

Fig. 7. An orthophoto image of September 12th with loci and artifacts running inside ArchField C++.

A. Level-of-Detail Approach to Digital Archaeological Data

In order to efficiently manage massive datasets three different 3D culling methods were developed to decrease the Level of Detail (LOD) of 3D datasets as the view changes. The varying LOD breaks the data into readable chunks at the highest resolution and produces a number of levels of lower resolution models when there is a far rendering distance. Only data required to efficiently fill the pixels of the viewing window need to be loaded, significantly reducing the amount of data that needs to be rendered every frame. This allows faster rendering on less powerful GPU and removes almost zero loading time for models when switching from one to another.

There are various methods to create an LOD version of a model. The most common method involves the subdivision of the model into different spaces with the generation of multiple levels of reduced detail (greater simplification) that are view-distance dependent. A number of different sub-division techniques can be applied but the most common forms take a tree like data structure (e.g. a quadtree, octree, R-tree, BSP). In the current implication, Binary Space Partitioning (BSP) is used for the point clouds, since it was found to work well with the irregular data structure of the point cloud using hints from the OSG rendering engine to determine the hyperplanes (fig 5). Quadtree sub-division is used for 3D meshes with high resolution textures and orthophotos/DEM (figs. 6-7). Since 3D rendering is handled inside OSG the LOD models are stored in a standard binary format and loaded into the background on a separate thread only becoming visible once they are fully loaded, this method is called Paged LOD in OSG.

The pre-computation of all the point clouds, models, and orthophotos has allowed an unlimited rendering of multiple sets of models generated from the KAJ SfM datasets with an accumulation of rendered models that can far exceed over 1 billion points or triangles. This method allows all the different days of excavation to be loaded at the same time and users can switch models on and off with no noticeable lag in the software.

B. Drawing and Annotating Top Plans in 3D

Editing top plans and point clouds in a 3D environment is not a trivial task. Popular software such as Meshlab, AutoCAD, 3DSMax are typically very difficult tools to use when it comes to 3D point selection. A novel solution integrated into ArchField for drawing and annotating in 3D space on top of these models is to compute the casting of a ray from the user's mouse and calculate its intersection on the point cloud or mesh. The closest vertex is found by iteratively cycling through all nearby points until the one closest to the ray is found. This approach allows the user to efficiently draw on top of the 3D models only selecting the closest point to the eye-view of the user. Once rotated the user can see that the point from a point cloud is selected irrespective of distance from the viewer and the parallax of a 3D view. Once a point is selected the user can either record more points, draw isolines, polygons, or pin an annotation.

C. Multi-DBMS Integration: SQL + NOSQL

Since the first version of ArchField, PostGIS has been used as the primary DBMS. PostGIS has a suite of GIS based tools for spatially querying and re-projecting data. However, now that the same libraries used in PostGIS can similarly be integrated into ArchField, a number of these features can be applied to other non-GIS enabled databases. A major drawback of PostgreSQL is that it has no built in revision control and it does not allow syncing tables from a local to remote database. Since most data entry in the field is done offline from the home server, this can lead to unchecked conflicts and has required the development of extended tools in ArchField to address these issues. In contrast, NoSQL databases such as CouchDB have built in revision control and syncing out of the box. Since other software associated to ArchField called OpenDig (www.opendig.org) directly stores and syncs loci information to CouchDB, we decided it would be advantageous to support such a versatile database. Therefore, an entire class was created in ArchField C++ to make the core software, PostGIS and CouchDB interoperable. Query results from PostGIS can be converted into JSON formatted data for CouchDB and vice versa.

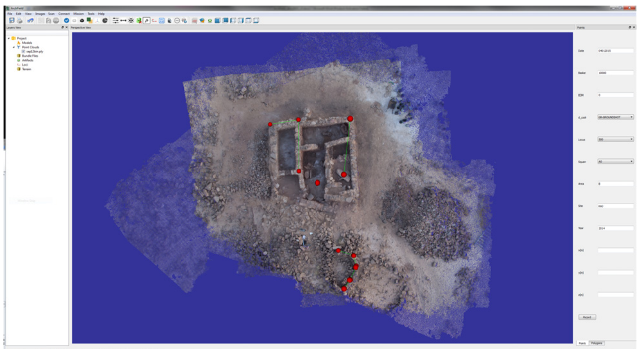

Fig. 8. The ArchField C++ interface with snapped points and lines to the point cloud of September 12th.

VII. Conclusions and Future Work

ArchField C++ allows any archaeologist to take field recording to the 4th dimension. It is the first fully developed software package designed for archaeologists that enables time-lapsed viewing of massive 3D point clouds, textured meshes and orthophotos. These datasets can not only be viewed but edited, annotated and drawn on top of by archaeologists. A 4D Top Plan can now be viewed in real-time using ArchField C++. The software incorporates a multi-DBMS system with both SQL and NOSQL formats.

It has been argued in this paper that in order for a software to be considered a 4D GIS recording software it must meet specific objectives not only in being able to render 4D scans of sites in relation to other spatial datasets but possessing tools that enhance analytics and annotation of these datasets. Four dimensional time does not just refer to the stratigraphic layers of a site but also includes post-depositional processes and the practice of excavating the site itself. The current version of ArchField C++ is a significant step forward in meeting these objectives.

The future direction of ArchField C++ will focus on developing a larger suite of tools for refining the definition of recorded Loci layers and more intuitively annotating and querying finds. A powerful tool in the future will be the ability to easily segment out in-situ artifacts and features from the daily SfM sets and store them as independent spatially oriented models. Automated referencing of new SfM sets to previously geo-referenced SfM sets using image matching appears to be the most effective method towards solving the ongoing back-log problem faced from the 2014 excavations. Additionally, a better SfM processing pipeline running on several workstations setup in the field appears to be the only solution to address the compute limitations of the backlog. Finally, in order to accelerate ArchField's development the authors intend to make the software available to the archaeological community in the near future where it can be tested and refined through user input and annual workshops.

Acknowledgment

This project was funded in part by NSF IGERT and King Abdullah University of Science and Technology. We are grateful to the Department of Antiquities of Jordan, Dr. Mohammad Najjar, and the 2014 ELRAP staff and students. The computation of the LOD for the point clouds would not have been possible without the excellent work by Philip Weber and the UCSD Immersive Visualization Laboratory.

References

[1] G. Agugiaro, F. Remondino, G. Girardi, J. von Schwerin, H. Richards-Rissetto, and R. De Amicis, "A web-based interactive tool for multi-resolution 3D models of a Maya archaeological site." Proceedings of the 4th ISPRS International Workshop 3D-ARCH 2011: "3D Virtual Reconstruction and Visualization of Complex Architectures" Trento, Italy, 2-4 March 2011. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVIII-5/W16 (on CD-ROM), 2011.

[2] P. Allen, et al, "Digitally modeling, visualizing and preserving archaeological sites," Proc. Joint Conference on Digital Libraries 2004 (JCDL 2004). Tuscon, AZ. June 7–11, 2004, 2004.

[3] M. Auer, G. Agugiaro, N. Billen, L. Loos, A. Zipf, "Web-based Visualization and Query of semantically segmented multiresolution 3D Models in the Field of Cultural Heritage," in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II-5, doi:10.5194/isprsannals-II-5-33-2014, pp. 33-39.

[4] Å. Berggren, N. Dell'Unto, M. Forte, S. Haddow, I. Hodder, J. Issavi, N. Lercari, C. Mazzucato, A. Mickel, J. S. Taylor, "Revisiting reflexivearchaeology at Çatalhöyük: integrating digital and 3D technologies at the trowel's edge," Antiquity,89, pp 433-448, 2015.

[5] G. Fabricatore, and F. Cantone. "Pushing the Archaeological Interpretation by Analysing Workflow Protocols: The "Variable Transparency Image Stacker" and DATARCH© Archaeological Data Management System," Layers of Perception – CAA 2007, 2007.

[6] M. Forte, "Virtual Reality, Cyberarchaeology, Teleimmersive Archaeology," in Campana S., Remondino F., 3D surveying and modeling in archaeology and cultural heritage. Theory and best practices. BAR ARCHAEOPRESS, Winter, 2013.

[7] M. Forte, and G. Kurillo. "Cyberarchaeology: experimenting with teleimmersive archaeology," 16th International Conference on Virtual Systems and Multimedia (VSMM), pp. 155-163, 2010.

[8] E. Gay, K. Galor, D. B. Cooper, A. Willis, B. B. Kimia, S. Karumuri, G. Taubin, W. Doutre, D. Sanders, and S. Liu, "REVEAL Intermediate Report," Proceedings of CVPR Workshop on Applications of Computer Vision in Archaeology (ACVA'10), June, 2010.

[9] D. Gorton, R. Shen, N. Srinivas Vemuri, W. Fan, E. A. Fox, "ETANA-GIS: GIS for Archaeological Digital Libraries." In JCDL'06, June 11–15, 2006, Chapel Hill, North Carolina, USA, 2006.

[10] B. Huang, Y. Han, C. Ma, C. Wang, and G. Chen. "Ancient ruins real-time interactive system based on VR-GIS platform," International Conference on Computational Intelligence and Software Engineering, 2009, CiSE 2009, pp. 1-5,11-13, 2009.

[11] M. Katsianis, T. Spyros, K. Kotsakisa, A. Kousoulakoub, "A 3D digital workflow for archaeo-logical intra-site research using GIS," Journal of Archaoelogical Science, 35 (3), 655–667, 2008.

[12] S. Al-Kheder, Y. Al-shawabkeh, and N. Haala. "Developing a documentation system for desert palaces in Jordan using 3D laser scanning and digital photogrammetry," Journal of Archaeological Science 36:537-546, 2009.

[13] G. Kurillo, M. Forte, and R. Bajcsy. "Teleimmersive 3D collaborative environment for cyberarchaeology," 2010 IEEE Computer Society

Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), pp. 23-28, 2010.

[14] T. E. Levy, and N. G. Smith. "On-site digital archaeology: GIS-based excavation recording in southern Jordan," in Crossing Jordan--North American Contributions to the Archaeology of Jordan, T. E. Levy, M. Daviau, R. Younker and M. M. Shaer, Eds. London: Equinox, 2007, pp. 47-58.

[15] T. E. Levy, et al. "On-site digital archaeology 3.0 and cyber-archaeology: Into the Future of the Past – New Developments, Delivery and the Creation of a Data Avalanche," in Introduction to Cyber-Archaeology, M. Forte, Ed. Oxford: Archeopress, 2010, pp. 135-153.

[16] T. E. Levy, N. G. Smith, M. Najjar, T. A.DeFanti, A. Y. Lin, and F. Kuester. Cyber-archaeology in the Holy Land - the Future of the Past. Washington, D.C.: Biblical Archaeology Society eBook, 2012.

[17] J.F. Montesinos, C.L. Lopez, F. M. Rangel Pardo. “ArchaeoloGIS: Using Geographic Information Systems to Support Archaeological Research,” in COM.Geo 2010, June 21-23, 2010 Washington, DC, USA, 2010.

[18] V. A. Petrovic, A. Gidding, T. Wypych, F. Kuester, T. A. DeFanti, and T. E. Levy. "Dealing with archaeology's data avalanche," IEEE Computer Society, July 2011, pp. 56-60.

[19] M. Pollefeys, L. Van Gool, M. Vergauwen, K. Cornelis, F. verbiest, J. Tops. “Image-based 3D Recording for Archaeological Field Work,” Computer Graphics and Applications (CGA). 23(3): 20-27, 2003.

[20] K.A. Ross, A. Janevski, and J. Stoyanovich. “A Faceted Query Engine Applied to Archaeology,” in Proceedings of the 31st VLDB Conference, Trondheim, Norway, 2005.

[21] N. Smith, K. Knabb, C. DeFanti, P. Weber, J. Schulze, A. Prudhomme, F. Kuester, T. Levy, T. DeFanti, “ArtifactVis2: Managing real-time archaeological data in immersive 3D environments,” Proceedings of IEEE 19th Int’l Conference on Virtual Systems and Multimedia (VSMM 2013).

[22] N. G. Smith, T.E. Levy, “Archfield: A Digital Application For Real-Time Acquisition And Dissemination – From The Field To The Virtual Museum,” Mediterranean Archaeology and Archaeometry 14 (4):65-74, 2014.

[23] N. G. Smith, L. Passone, S. al-Said, M. al-Farhan, T.E. Levy, “Integrated Data Capture, Processing, and Dissemination in the al-Ula Valley, Saudi Arabia,” Near Eastern Archaeology 77(3): 176-181, 2014.