Reverse Engineering of Scale Models Using Dataflow Programming

Application to the fortification of plans-reliefs

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***Abstract*—Despite the progress in three-dimensional scanning, some architectural artifacts remain a digitizing challenge. Scale models and more especially the plans-reliefs of Louis XIV of France have specific characteristics such as size, scale, number, etc. A knowledge-based modeling approach is developed to address the limitations of digitizing tools. Our study deals with the fortified areas of the scale models. Bastioned fortification works extend over wide areas but they are built according to design rules. Once studied and organized, fortification knowledge has been used to create a library of parametric components. Implemented in Grasshopper, the components were manually adjusted to different practical cases. The library was then validated and we are now focusing on the automation of the adjustments of the components. Thereupon a reverse-engineering approach has been set up. Semantic segmentation algorithms have been defined and implemented in Grasshopper to automatically extract fortification features from 3D surveys based on the knowledge of fortification design rules.**

Along with the three-dimensional modeling of fortification, an automatic reconstruction of the city parts of the scale models is underway. Both these studies are part of a project aimed at valorizing and diffusing a very unique cultural heritage collection. As such, knowledge models are precious assets both the digitizing and the semantic enhancements of the final application.

***Index Terms*—architectural heritage, parametric modeling, reverse-engineering, architectural knowledge, scale models, 3D surveys.**

I. Introduction

A. Context

The scale models of the French collection of Plans-Reliefs[1] are an example of the variety of our architectural heritage. These three-dimensional representations of fortified places were first ordered under the reign of Louis XIV of France. The collection would increase up to a maximum of 260 plans-reliefs since the late 17th and for two centuries. Because of the geography of the French borders, the sizes and shapes are very different from a fortified place to another and so are the plans-reliefs (Fig. 1). Today, of the remaining hundred models, only 40 percent is displayed in museums.

The creation of virtual remote accessed scale models may resolve access issues. A virtual model which is accessible via internet by the largest public can allow the end user to access plans-reliefs rarely seen and/or parts of them usually invisible. Moreover, a virtual collection of plans-reliefs can become a medium for documentation once linked to data bases or other digital collections.

However, scale models and in particular the plans-reliefs present specific problems when it comes to digitize them. 3D surveys are not precise enough for many reasons. Typical problems such as sim precision of edges acquisitions or occlusions are amplified by the scale of the models – 1 to 600 – as the level of detail and the density of elements are very high. The size of the scale models – up to 160m² but around 20m² on average – may also be a handicap given that some of the most densely area are find in the center of the model where accessibility is limited. Finally, some plans-reliefs or parts of plans-reliefs are in bad conditions as a result of wear and tear. The numerous moves of the collection, the materials used to make the models (silk, paper, lime-wood, etc.) and the lack of protection measures make it necessary regular restoration works.

Fig. 1. The 48 parts of the plan-relief of Brest (130m²) being installed for the exhibition "La France en Relief" at the Grand Palais in Paris. © ECPAD

[1] www.museedesplansreliefs.culture.fr/

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B. Overview of the paper

In this the paper we present a reverse engineering approach for the 3D modeling of fortification sites of the scale models of the French collection of Plans-Reliefs. After an overview of related works in scale models digitizing in section II, the project background and the overall approach will be described in section III and IV. In section V, the implementation of this approach, the experiments and the results will be presented. Finally, we will conclude on the raw data semantic segmentation thanks to Grasshopper and its strengths in reverse engineering.

II. Related Works

These last years, many projects dealing with historical scale models digitizing have been conducted. Most of them use scale models only as a documentary source among other data such as maps, texts or surveys of the current state of cities [1] [2] [3]. The aim of these projects is not the creation of a virtual replica which has to be faithful to the original historical model but essentially the development of historical SIG. Thanks to historical scale models, one single source provide all the information required to create a virtual model of a city as it was at the time depicted in the physical models. In these kinds of projects, the existence of a scale model is a precious asset but the data acquired by three-dimensional scanning are mostly used to support manual modeling, giving graphic designers a rough 3D model.

Nonetheless, some of these projects try to automate data treatments in order to speed up the reconstruction process because of the thousands of buildings that have to be reconstructed. Once formalized, architectural knowledge can allow features extraction for the automatic reconstruction of virtual replicas of scale models [1] [4]. Rome Reborn [5] stands out from these last projects given the fact that the survey data of the "Plastico di Roma" were used as input parameters in a shape grammar based procedural modeling process [6]. In this case, architectural rules from theoretical literature are translated into modeling rules. These rules operate on shapes deriving from the surveys data and quickly generate a large quantity of models.

Finally, it should be noted that some works have also been done in the digitizing of scale models from the collection of Plans-Reliefs but none of them aimed at making virtual replicas of the original scale models [7] [8].

III. Project Background

The digitizing of plans-reliefs is a project that has already leaded to promising results in the automation of buildings reconstruction from data surveys thanks to the use of architectural knowledge [9]. This approach had been then applied on the fortified areas as they obey to specific design rules too.

A. Study of bastioned fortification treatises

In a great majority of cases, fortification areas are divided in fronts. Each front may be composed of several works which are identifiable and designed thanks to regulating lines. Every front is composed of at least one city wall which is the first to be build (Fig. 2, a). This wall is called a bastioned front when its line is made of two faces, two flanks and a curtain. In front of the city wall, outworks may support and shield the main wall. For example, there are the demi-lune and the tenaille (Fig. 2, b and c) which are built upon the main wall. The covered way (Fig. 2, d) is the final work. It is a broad lane covered by a breastwork like the others works and its design is based on both the main wall and the outworks (demi-lune and tenaille).

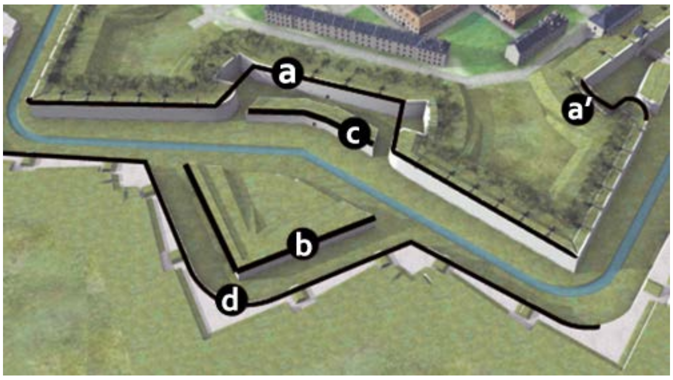

Fig. 2. A bastioned front and its most common works and their regulating lines: the city wall (a) line which can have orillons (a') (era-shaped projection at the flank of bastions), the demi-lune (b), the tenaille (c) and the covered way (d) lines. © Art Graphique & Patrimoine

In a previous paper [10], we already showed that bastioned fortification works are designed, sized and located to protect each other and to minimize dead spots. These works obey design rules which were theorized in architectural treatises. These theoretical regulating lines are "used to control proportion and placement of elements" [11]. They are nothing more than trajectories along which 2-dimensional profiles are swept orthogonally. More than 80% of bastioned works are designed thanks to this principle and the remaining 20% consist of smaller and/or unusual bastioned works.

B. A parametric library of bastioned fortification works

The MAP-Crai have developed a significant experience in parametric modeling for cultural heritage through specific tools like POG [12]. To test and extend this competence to the modeling of the fortification areas of plans-reliefs, it was decided to create and use a library of components consisting of regulating lines, profiles and sweep operations. At first, the adjustments of the components were manual but as we will see in the following sections, we are now able to automate this step.

C. Grasshopper implementation and continuum

Grasshopper is a visual dataflow programming language (VDPL) editor. Unlike parametric modeling language such as GML [13], MEL [14] or JavaScript [15], VDPL do not require any textual programming skills whereas they can achieve the creation of complex 3D parametric scenes in short time span and " efficiently explore alternative forms without having to manually build each different version of the design model for each scenario" [16]. Thus, users with basic knowledge of geometry 3-dimensional modeling can specify a sequence of relationships and operations to automate the construction of geometry in the form of links and nodes. The operations have parameters with values that can be manually adjusted depending on the situation.

Originally intended to architectural designers, Grasshopper goes now beyond architecture concepts field towards responsive technologies, robotics, etc. but also, as we will demonstrate, to cultural heritage digitizing issues.

D. Experiments and validation of the library

Once the main fortification trajectories and profiles are implemented in Grasshopper (Fig. 3), the library of parametric fortification components is tested on a representative sample of fortification sites. However, the samples are restricted to plain sites given that mountain sites are too irregular to be modeled thanks to a parametric process.

Each work was then manually adjusted onto the available data sources (3D surveys, maps, preparatory documents of the scale models, etc.) from the main wall lines and the outworks (demi-lune and tenaille) to the covered way lines as these lines are relatives to each other. This was highlighted by the validation process of the parametric library. Indeed, it shows that the more we advance in the modeling process, the more the accuracy of the reconstruction is dropping [17].

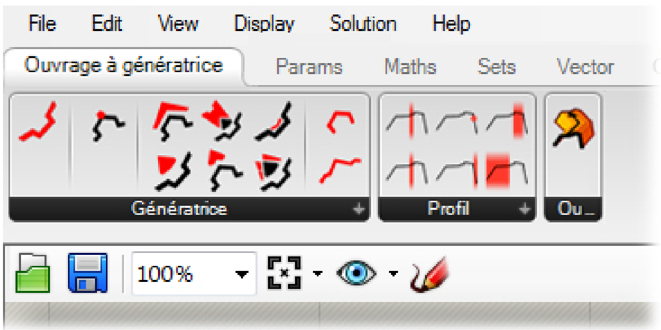

Fig. 3. The new fortification shelf in Grasshopper and its different sub tabs (from left to right): trajectory, profile and sweep operation.

IV. KNOWLEDGE BASED APPROACH: FROM SCALE MODEL TO 3D REPLICA

To compensate for the limitation in the data acquisition and in order to automate and speed up the reconstruction process of the fortification from plans-reliefs, a knowledge-based approach has been set up. Already described, the first step was the study of fortification treatises and the modeling of fortification knowledge. The creation of the parametric library and the manual adjustments of its components onto the 3D surveys are all done in Grasshopper. So far, the components were manually adjusted that is why we develop a new process for automatic adjustments that is part of the main approach. The resulting prototype tool Kastor (Fig. 4) – for Knowledge-based Approach: from Scale Model TO 3D Replicas – is tightly integrated in Grasshopper. It now includes the parametric library, the semantic segmentation and all the following processes required to model the fortification works.

As described in figure 4, the surveys of plans-reliefs had to be meshed before being imported in Kastor. It is only then that the semantic feature extraction process can be initiated. A first step is the geometric feature extraction of segments. Next, the fortification knowledge is used to cluster these segments according to the bastioned works they are part of. Among these clusters, a set of segments are identified according to specific constraints of position and size. Thus, we identify the trajectories for each fortification works.

In the automatic adjustment step, the trajectories are used as input parameters for the components of the parametric library. In this way, we retrieve the values of the parameters required to create the fortification works like in reverse-engineering process. Up to this stage, Kastor do not require user interventions but manual adjustments are an option kept open for cases where automatic adjustments are imperfect.

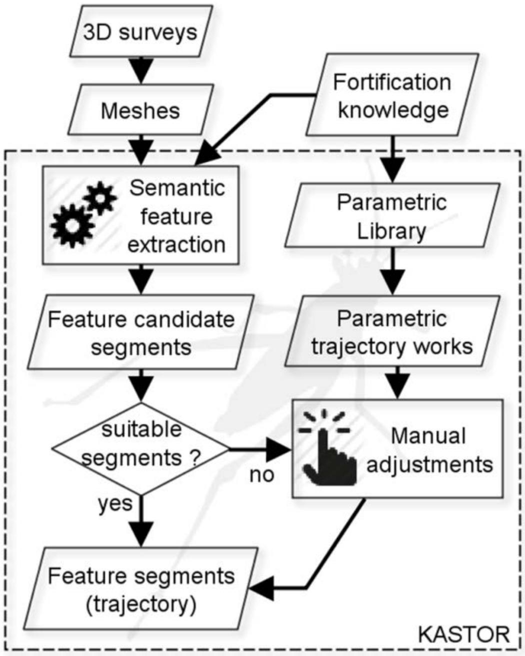

Fig. 4. Flowchart of the trajectory extraction process in Kastor. The surveys are meshed before being used in the semantic feature process along with specific knowledge in order to retrieve the trajectories of bastioned works.

V. AUTOMATIC ADJUSTMENTS

Reconstruction process has to be robust whatever digitizing method is used to scan the scale models. According to the conservation or exhibition sites and depending of the size of the scale models, some methods are not possible.

Moreover, after a series of tests with specialized software programs like Geomagic Studio or Rapidform XOR, a geometric features extraction process in Grasshopper was set up because the results with the above-cited reverse-engineering applications were far from satisfactory unlike the tests done in the city parts [18].

A. Diversity of the origins of the 3D surveys

In the first stage of the features extraction process the fortifications of plans-reliefs have to be digitized. However, more than half of the hundred plans-reliefs are not on display in museums. Most of them are stored in warehouses outside Paris. The others are presented in air-conditioned cases which make access to the scale models even more difficult.

As a result of these logistical constraints, we have to rely on different digitizing methods according to the place of exhibition or storage. We may also rely on the sparse data available that can be provided by other actors involved in plan-relief digitizing. Given that raw data might not share the same characteristics, our approach has to be robust to turn a problem into an asset.

For now, we have three partial 3D surveys of the plans-reliefs of Marsal, Strasbourg and Toul. The resulting surveys, as we will see, are of different quality both in terms of theoretical point density and homogeneity of the resulting triangulate network.

The data acquisition for the plan-relief of Marsal has been made by Art Graphique & Patrimoine (2013) with a Konica Minolta Vivid laser scanner with an estimated precision of 1.5 mm and a highly irregular triangulated network (Fig. 5.a). It is important to note that the project conducted by AGP was aimed at making a virtual model of the town of Marsal and not to create a virtual replica of its plan-relief. The plan-relief of Strasbourg was digitized thanks to Autodesk 123D Catch software with a higher estimated precision – around 0.5 mm – but the resulting mesh is also highly irregular (Fig. 5.b). Finally, the scanned data of Toul were obtained using a Handyscan handheld scanner at a precision of 0.5 mm with a homogenous triangulated network (Fig. 5.c). Therefore, we have a varied sample groups of meshes on which we can directly test our segmentation algorithms.

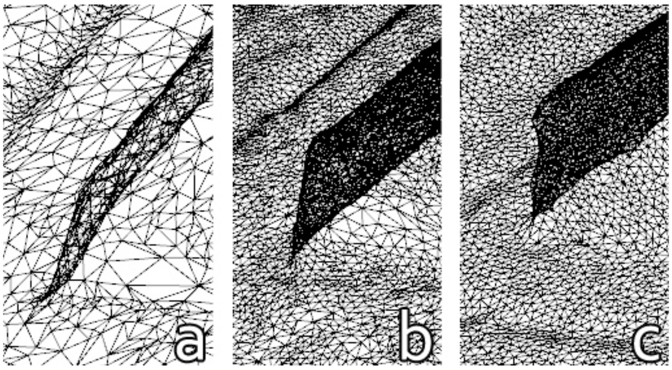

Fig. 5. The fronts of a bastion in the meshes of, a: Marsal (Vivid), b: Strasbourg (123D Catch) and c: Toul (Handyscan).

B. Fortification features extraction in Kastor for Grasshopper

The first step in the fortification features extraction is the extraction of segments from the meshes. They are automatically intersected by horizontal planes to extract contour lines which are projected onto a single horizontal plane. For the next operations to work, it is necessary to convert the contour lines from polylines to segments.

The features extraction process for the extraction of the trajectories can be described in two levels: bastioned work level and bastioned work lines level. Both level principles will be illustrated with the case of the tenaille work.

1) Bastioned work level

The semantic (or fortification) features extraction process is based on fortification knowledge. Thanks to design rules, bounding surfaces are created for every fortification works. The intersections of each bounding surfaces with the segments of the contour lines give us as many clusters of segments as there are fortification works. Indeed these clusters of segments are part of the fortification works.

The execution of the bounding surfaces must occur in sequence, and the next execution cannot occur until the previous one has been completed. As a general rule, in order to create the bounding surface of a fortification work – belonging to a rank “r” – that will in turn allow us to retrieve its trajectory, it is necessary to have the trajectory of the fortification works of rank “r-1”. For example, the main wall is referred to as a work of rank 0, the demi-lune and the tenaille as works of rank 1and the covered way as a work of rank 2. Indeed, the outworks (demi-lune, tenaille, etc.) need the main walls to be built and the covered way needs both the outworks and the main walls.

The further the fortification works are from the main walls, the more numerous the works depending on may be. Based on this principle and on fortification design rules, the fortification work trajectory of the main wall will lead to the automatic creation of the following outworks (i.e. the demi-lune and the tenaille) bounding surfaces. Finally, the bounding polygons of the covered way will be created based both on the trajectories of the outworks and the main walls.

However, to create the bounding surface of the first work (i.e. the main walls), we need a manual intervention to place reference points corresponding to the ends of the main walls (Fig. 6, A and B). First, based on these points, a theoretical trajectory of the main wall is automatically created thanks to the design rules found in treatises. Then, a polygonal surface is created from the theoretical wall to ensure the presence of all the segments forming the main wall in the resulting cluster.

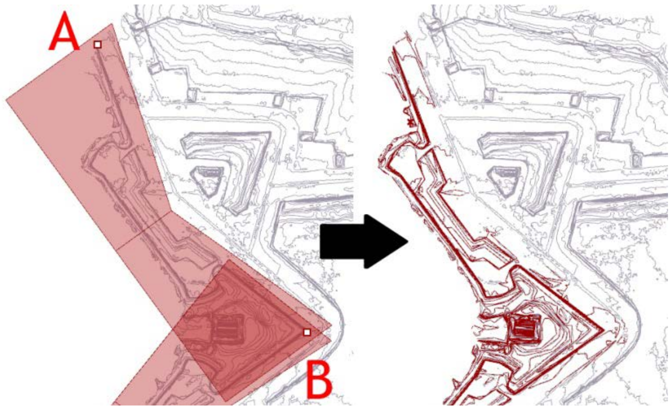

Fig. 6. The creation of the clusters encompassing the segments of the main walls

2) Example with the tenaille work

In this example, the main wall line trajectory has already been retrieved by using the method described in the previous section. We can now use the design rules such as in figure 7 to create a bounding surface given the fact that the design of the tenaille trajectory (ILNOMJ in figure 7) is based on the previously recovered main wall line (ABCDEF in figure 7).

Once the bounding surface is created (Fig. 8a) based on previous reference geometries (i.e. the main wall in green), we intersect the contour lines extracted from the mesh with the bounding surface to create a cluster of segments encompassing the trajectory of the tenaille work.

3) Bastioned work line levels

Having clustered the segments according to the fortification work trajectory they are part of, we identify the different lines of the works trajectory – such as faces, flanks or curtain – thanks to their geometrical properties described in the knowledge model. For each line, a first bounding surface is created to cluster the segments inside the work bounding surface to retrieve one after the other the faces, the curtain and the flanks of the work.

Again, the operations have to be done in sequence for each work; the curtain cannot be retrieve without the faces and the flanks without both the faces and the curtain.

4) Example with the faces of the tenaille outwork

We now have a cluster of segments belonging to the tenaille work. Based on these, we create again a bounding surface. It is smaller as it is only intended to encompass the set of segments belonging to the faces (BL and MJ in figure 7) of the tenaille. The shape of this last bounding surface is based again on the design rules of the faces of the tenaille work (Fig. 8b). Then, length and position constraints remove most of the incompatible segments such as outliers in figure 8c. At last a final Grasshopper algorithm fit an average line onto the last set of segments (Fig. 8d).

These lines are the faces of the tenaille. They will be added to the reference geometry set of lines for further lines and trajectory extraction. Thus, in the next stage, the faces will be used with other reference geometries to retrieve the curtain of the flank. This operation will be repeated once again to recover the flanks and all the lines will be joined to create the whole trajectory of this outwork.

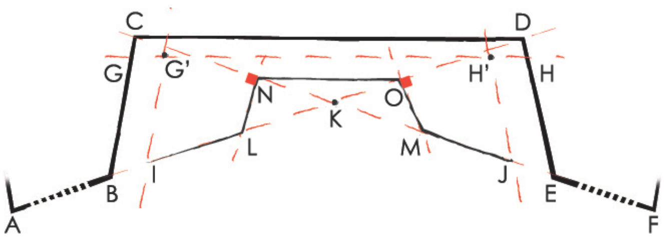

Fig. 7. The tenaille trajectory design rules show the relations between the outwork and the main wall ABCDEF. For example, the faces (IL) and (EF) of tenaille are part of the lines (AB) and (EF) of the main wall. The curtain of the tenaille (NO) is parallel to the curtain of the main wall (CD).

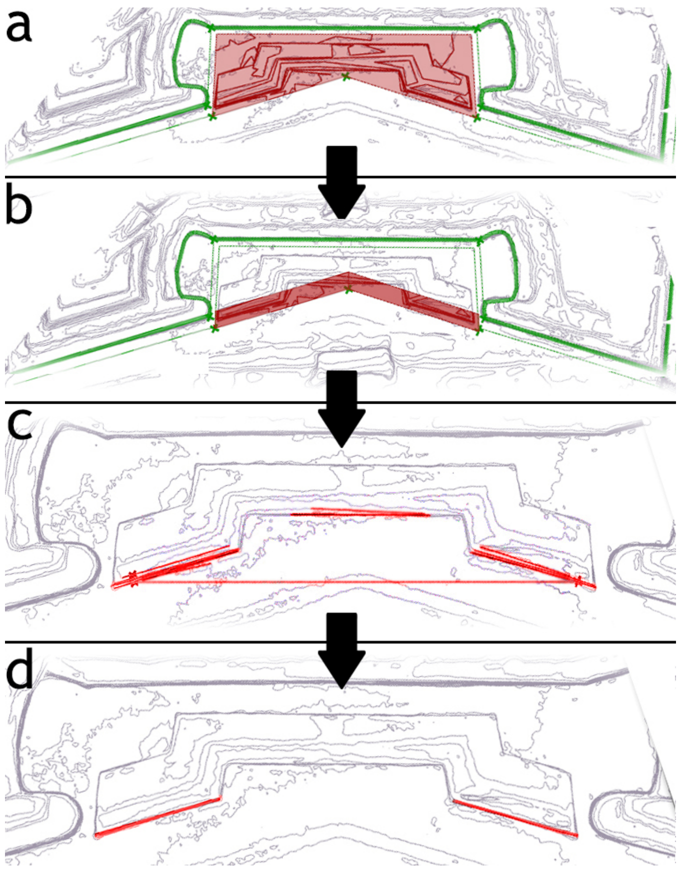

Fig. 8. The different steps for the extraction of a set of segments and the ajustment of an average line based on the cluster of segments of a tenaille

C. Results of the features extraction

Even if we have conducted the experiments on three partial 3D surveys, the different quality of the meshes and the various fortification works of the plans-reliefs of Marsal, Strasbourg and Toul are enough to make a first assessment on the features extraction process with Kastor. In order to evaluate the accuracy of the segmented trajectory, we use a method that is identical to the one used for the validation of the parametric library [17]. It consists of comparing the evaluated trajectory to a reference line that has a 2 millimeters buffer zone on each side of it. In this case, the evaluated data is the segmented trajectory whereas the reference line is a perfect trajectory that has been manually adjusted to the plan-relief fortifications.

The following table highlights the effectiveness of the approach since all the trajectories of the surveys have been retrieved. Whatever the digitizing method (lasergrammetric or photogrammetric) and the accuracy of the survey, we are able to fulfill all of the goals of the approach.

Besides, the good results on the survey of Marsal which is a low density mesh allow us to work now with smaller files for further projects may be considered, thus speeding up the processing time. Moreover, the results for the plan-relief of Strasbourg demonstrate the capacity of recent photogrammetric tool to generate reliable data: once processed, they give as good results as laser scanned data. Thus, photogrammetry offered a powerful alternative to laser scanner given that it is also easier to operate in areas where plans-reliefs are located.

Site		Fortification Works			
Name	***Size in triangles***	***Main wall***	***Demi-lune***	***Tenaille***	***Time (s)***
Marsal	392 021	90.4%	70.6%	n/a	12,8
Toul	1 105 541	94.6%	99.2%	n/a	5,9
Strasbourg	2 374 563	96.7%	92.7%	97.6%	26,2

Table 1. Accuracy of the segmented trajectories and processing time for the meshes of Marsal, Toul and Strasbourg.

D. Reverse-engineering of the fortification

The fortification components of the parametric library are all composed of two parts like the main wall trajectory in Figure 9. The first one is a Grasshopper algorithm for creating a fortification work trajectory with theoretical parameters and values (a). The second part is a specific adjustment component for this fortification work trajectory (c). It allows us to change the values of the parameters of the wall. During the previous approach, the manual adjustments were done thanks to this component combination: the theoretical trajectory component being used as a parameter of the adjustment component.

Now, we can replace the theoretical trajectory (Fig. 9.a) input parameter of the adjustment component (Fig. 9.c) by the trajectory resulting of the semantic feature extraction process (Fig 9.b). With the benefit of a more accurate input parameter, manuals adjustments become rare and minor.

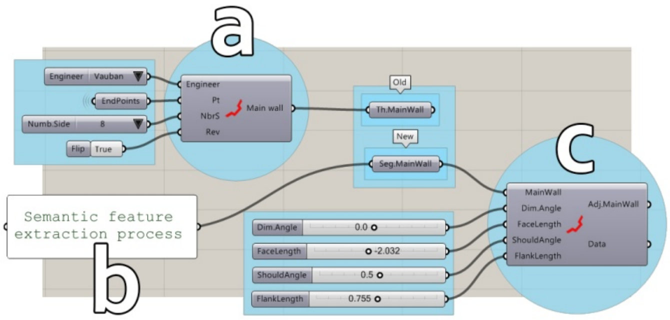

Fig. 9. The adjustment component for the main wall trajectory (b) was linked to the main wall trajectory component from the parametric library (a). Now, thanks to the semantic segmentation of the survey based on the knowledge model, it can be linked to a segmented trajectory (c), which requires much less adjustment

Even if for the three surveys of Marsal, Strasbourg and Toul, the segmentation is a success, we keep the possibility to perform final adjustments on the trajectories for future situations where the segmentation failed to achieve satisfactory results.

VI. Conclusion And Future Works

In the field of cultural heritage, scale-models are objects which increase most of the known issues in digitizing projects. Accessibility, level of detail, size, wear and tear, etc. induce huge quantities of raw data and a high proportion of incorrect or missing information as well as overload of information. One possible solution is to use a knowledge-based approach to address these problems.

A reverse-engineering approach has been set up. From the 3D surveys, we extract 2D fortification features thanks to a precise knowledge modeling of this military architecture. By retrieving fortification regulating lines, we actually have the trajectory parameter of sweep operations. Once associated with a profile, it is possible to model in 3D most of the fortification works of bastioned fortification field.

The use of the parametric strengths of Grasshopper in areas remote from its initial function such as cultural heritage is now fully validated. More than just a parametric library, it is a full reverse-engineering approach that has been implemented in the Kastor plug-in.

Work continues in Kastor to improve and complete the current approach. Reusable, abstract parts are a keystone of parametric design [19] and so in reverse-engineering. Reverse-design patterns are already being studied in order to explore generic solutions. As such, it is possible to extend our approach to fortifications of other scale models and even to other parts of scale models (buildings i.e.), provided the knowledge model is adapted accordingly. Once the experimentations in cases as difficult as scale models are validated, we will be able to test the approach on life-size objects in a confident manner.

To retrieve the trajectories of every fortification works in Kastor, we had to create new operation objects – known as components in Grasshopper – to process clusters of segments. The current components can be improved given their proximity to research issues like 2D lines simplification that are still under assessment.

Moreover, some experimentation is already carried out for the 3D modeling based on profiles extraction (Fig. 10). We are nearing completion of full 3D reconstruction of bastioned works thanks to a generic sweep process for all the retrieved trajectories.

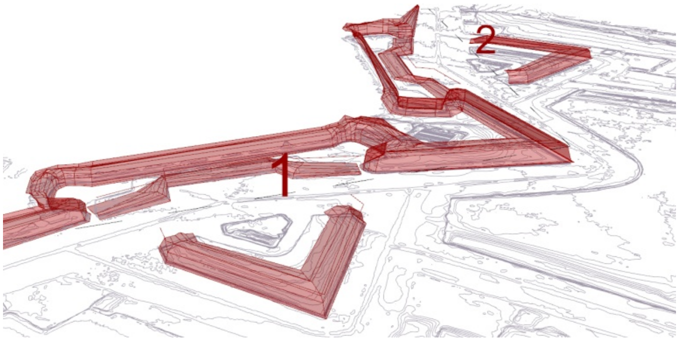

Fig. 10. First attempt at automatic profile extractions and 3D sweep operations

Acknowledgment

The three-dimensional acquisition and meshing of the plan-relief of Marsal were conducted by Art Graphique & Patrimoine[2].

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