Study of the Fortification of old scale models in order to automate their 3D modelling

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Abstract. The creation of virtual models of Plans-Reliefs (sometimes called relief maps) is a project to preserve and to make known masterpieces of European Cultural Heritage. In this paper, we present the first experiments carried out in the automatic reconstruction of the fortifications modelled in every plan-relief. Their scale, size and state mean that digitising data alone is not usable. The study of historical documents like the many treatises of fortification allows us to fill in the gap by retrieving all the modelling information required in the creation of a library of parametric components with canonical values. These components are then adjusted according to theoretical ranges with a first set of reference documents like the plans that have been used by the original model makers.

Keywords. Virtual heritage; scale model; fortifications; parametric modelling, knowledge modelling.

INTRODUCTION

In recent years, 3D reconstruction through parametric approach has been an important research topic in the field of virtual heritage to address the gaps that may exist in digitised data. One of these lacks is their inability to deal with both a detailed and a large object like scale models (Guidi, et al., 2005) without recourse to numerous and costly devices (Remondino and al., 2009) [3].

The 3D modelling of plans-reliefs are among these projects. They are scale models of fortified places and were first ordered by Louis XIV's minister of war. Built over two hundred years from the late 17th to the late 19th century, the collection includes a hundred models whose sizes and shapes are very different. The only shared feature is that they exemplify the state of bastioned fortifications at different periods.

Our first test was carried out on the scale model of Toul in France (figure 1). Built in the middle of the 19th century, this plan-relief is one of the last to be made. Like the others, it is made of pieces or tables (the biggest is 2.31m x 2.23m). The scale is 1 to 600 but its size is quite large, nearly 40 m² (the average surface of the collection is around 20 m² whereas the biggest model is more than 150 m²). The model is in a bad state due to its fragile materials (silk, paper, lime-wood, etc.) and the lack of protection measures.
One of the intentions expressed by The Museum of Plans-Reliefs at Les Invalides [1] and the SRI (historical research centre) of Lorraine is to exhibit these delicate scale models thanks to 3D duplicates because most of the plans-reliefs are boxed in store-rooms where nobody can see them. Moreover, by creating a virtual model, we preserve a witness to the architectural, urbanism and fortification evolution which is intended to be widely diffused both to the general public and to researchers (Humbert, et al., 2011). It is therefore more than a simple digitising project since this project aims also at providing a medium able to offer links to online knowledge databases like the Base Mérimée [2].

The paper is organized as follows. Firstly, we present the issues in the making of virtual plans-reliefs and especially those concerning their digitising. Then, we introduce fortification science thanks to treatises. Their strengths and limitations are then synthesised before we focus on the principles governing fortification design. This knowledge allows us to experiment and modify several methods in our selected scale models. Finally, some results are presented and analysed in order to propose ways to improve the reconstruction process.

VIRTUAL PLANS-RELIEFS ISSUES

The method developed initially by Chevrier (2010) tried to include mostly automatic steps. Therefore, the reconstruction of nearly 4000 buildings was accomplished automatically with a minimal user help but the rest of the scale model, notably the fortifications was done manually. This is due to the fact that virtual reconstruction of scale models is complex because the acquisition and reconstruction steps lead to a plethora of drawbacks. Given the fact that there are more than a hundred scale models, we have to dispense as far as possible with interactive steps towards automatic processes to reduce the time, energy and any resources required to deliver all the 3D reconstructions.
But, it is unthinkable to use 3D scanned data alone as resulting point clouds are too large and present many holes and eroded edges. In addition, the points clouds cannot be easily segmented whereas in the 3D model, specific buildings like churches, cloisters, etc. should be selectable. At best, we can use laser and/or image-based data for mapping parametric components onto them to help in the adjustment of an object (Bae 2002; Murphy, et al., 2011; Luca, et al., 2011). Besides, we do not deal directly with reality but with a representation at the scale of 1:600. On this scale, details are plentiful, varied and unfortunately out of range of traditional acquisition technologies because some of them may be around a quarter of a millimetre, such as the carpentry. Furthermore, these models may be three hundred years old (the delicate materials suffer from bad preservation) and, as a result the restitution of damaged parts still requires man-made solutions through interactive interventions.

It should also be noted that most of the work done in 3D modelling of fortifications is usually carried out on single and full size models with the assistance of scanned or photogrammetric data and historical documents like old maps; it is the case for Brest [4], Iseubourg (Besselièvre & Art graphique et patrimoine. 2007) and Besançon [5]. There are also several 3D modelling projects of scale models but, as said in our last work (Chevrier, et al., 2009), they are not prone to having all the previous characteristics at the same time (scale models quantity, small scale, deterioration and semantic enrichment of the virtual model).

Finally, the previous points raise a question about the accuracy and the nature of the reconstruction. Uncertainties about the plans-reliefs remain, be it about their present or past states. Because of their current disrepair and the lack of documents about their initial state, any 3D model of plans-reliefs can only be an interpretation of what were the scale models at the time of their construction (Stefani, et al., 2011). Obviously, part of the uncertainties can be removed thanks to a better understanding of how fortifications work.

PRINCIPLES OF BASTIONED FORTIFICATION

Assets and limitations of treatises

“All Fortifications consist of Lines and Angles, which have various Names, according to their various Offices”. As implied by Chambers (Chambers 1728), bastioned fortifications are a science driven by strong geometrical properties which share complex hierarchical relationships. It is not surprising that engineers wanted to theorize their practices in architectural treatises. Their roles in 3D parametric reconstructions in the field of Cultural Heritage, and especially for ancient and classical architecture are undeniable, as evidenced by previous works (Chevrier, et al., 2009; Luca, et al., 2007). These treatises are quite similar to their civil or sacred counterparts with the only difference that they have not left their marks on architectural history (Orgeix 2009).

However, the amount of such historical documents is substantial in particular in France in the early 18th century. Their content is precious regarding engineers’ methods, construction steps, proportion rules and vocabulary (Lendy 1857). We do not only use these treatises for the semantic description, but above all for their proportion rules in order to create a library of parametric components based on historical data. Among the 350 ancient or recent works referenced by Balliet [6], we found no trace of a treaty by Vauban who never wrote such a document even though he intervened in most of the fortified places of France that have been made in plans-reliefs. To his mind, a treaty of fortification would have frozen the lines at the expense of the terrain.

Fortification construction process

Treatises teach us that each engineer has his own system (or method) for the creation of fortifications mainly because of artillery advances. Initially, we focused on twenty of the most cited engineers and at least as many systems. It is a standard practice in these treatises for an author to explain his system alongside the brightest engineers’ methods. Besides providing a good picture of the most widespread
systems, it also gives us access to Vauban’s methods since they are reported by others.

In a first selection of systems, it appears that the hierarchical structure of fortifications is inherent given that the whole fortification depends on a line called magistral. This regulating line corresponds to the delineation of the outer limits of all the bastioned fronts which include every flank and face of the bastions but also the curtains. Once the magistral is created, the rampart and the rest of the fortification (namely components like bastion, curtain wall, ravelin, bartizan, etc.) can be calculated from it (figure 2).

**The maximes**

The design of the magistral meets maximes (or principles). Engineers claimed that they must be regarded as the most important and essential rules of fortification. Ignore them and the fortification will contained imperfections. Engineers have worked out an immense range of systems to draw all the parts of bastioned fortifications according to these maximes. Unlike the methods, they are dictated by the range of the musket or the arquebus. For this reason, their values are immutable (table 1).

**The systems**

In each system, the magistral is drawn thanks to lines or angles like the line of defense, the flank, the face, the gorge, the exterior flanking angle, the angle of the circumference, etc. which have specific values according to the system. Note that it is not always the same lines that are involved in the different systems thus resulting in totally different geometrical constructions from one engineer to another. Indeed, we identified twenty-five construction lines and twenty kinds of angles that may be used among the ten or so systems we have already examined (figure 3).

![Table 1]

<table>
<thead>
<tr>
<th>Engineers</th>
<th>Errard</th>
<th>Cormontaigne</th>
<th>de Ville</th>
<th>Ozanam</th>
<th>le Blond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lengths</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face</td>
<td>/</td>
<td>≤ 60</td>
<td>/</td>
<td>/</td>
<td>35 → 50 → 60</td>
</tr>
<tr>
<td>Flank</td>
<td>≥ 16</td>
<td>≥ 15</td>
<td>1/6 side</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Defence</td>
<td>100 → 120</td>
<td>120 → 160</td>
<td>100 → 150</td>
<td>120</td>
<td>120 → 150</td>
</tr>
<tr>
<td>Demi-Gorge</td>
<td>&gt; 16</td>
<td>≥ 18</td>
<td>/</td>
<td>/</td>
<td>≥ 20</td>
</tr>
<tr>
<td><strong>Angles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>90°</td>
<td>/</td>
<td>/</td>
<td>≠ 90°</td>
<td>/</td>
</tr>
<tr>
<td>Bastion</td>
<td>90°</td>
<td>≥ 60°</td>
<td>90°</td>
<td>≥ 70°</td>
<td>≥ 60°</td>
</tr>
<tr>
<td>Flank</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>≠ 90°</td>
<td>100°</td>
</tr>
</tbody>
</table>

Figure 2
Some of the angles, lines, innerworks and outworks of a fortification.

Table 1
The maximes of five engineers we were able to find.
**FIRST EXPERIMENTS**

For our experiments, we use Grasshopper, the well-known generative modelling plug-in [7] as a prototyping tool because we are looking for fast drafts which do not require programming skills.

**Selection of plans-reliefs**

Our first tests are carried out on four scale models (Toul, Metz, Marsal and Verdun) summarising different degrees of regularity (figures 1 & 4). For the scale models of Toul and Marsal (32 m²), the fortifications...
are almost a regular polygon given the facts that there are no reliefs, rivers or previous fortifications to interfere with the magistrals. In contrast, for Metz (70 m²) and Verdun (50 m²) the surroundings are complex which lead to sprawling fortifications made of citadels and outworks. Thus, we have a contrasting sample group of models for which the dates of construction are close, restricting the number of the engineers that could have participated in the design of the fortifications.

**Selection and adaptation of the systems**
The systems of Pagan, Errard and Vauban are the first to be experimented. They are indeed the systems most commonly reported in prominent treatises such as those of Allain Manesson Malet (1691) and Louis de Cormontaigne (1741), considered to be Vauban's favorite and heir respectively. In the early 17th century, Errard was the first to lay down the rules of fortification in France. He is the one who make it a science. Studying his magistral allows us to lay the foundations of this discipline. As for Pagan, he is considered as the main source of inspiration of Vauban. Testing very similar and theoretical methods on practical cases will help us to determine how fairly close methods behave on irregular patterns.

The systems and their construction rules are established on regular polygons and, most of the time we only have to realize minor adaptations when we use them on the irregular patterns of plans-reliefs. However, when we have to deal with larger modifications, it is necessary to point out again the general functioning of bastioned fortification. Thus, if the magistral is the backbone of a bastioned fortification, then bastioned fronts are like its vertebrae. Flanking issues, which consists of suppressing all the blind spots of a fortified place are managed at the scale of the bastioned front (Lepage 2010). That is why magistrals have to be considered as nothing more than a succession of such fronts.

![Figure 5](image-url)

**Figure 5**
Adaptation of the Errard's system on irregular polygons: a) Centroids or the vertices of bisectors are unconvincing. b) Splitting the regular polygon (left) results in correct fronts (grey).
Errard used the centre of the external polygon for the creation of his magistral. Centroids are the closest point to the centres in irregular polygons but their use in the design of the magistral is not pertinent as the resulting line is in contradiction with the engineer’s maximes. In other tests, we use special lines like bisectors to determine the centres On, but the results are also unsatisfactory because they do not respect the maximes (e.g., the flank length has to be eighteen toises) (figure 5a).

Errard’s polygon must therefore be split into as many triangles as there are sides in its figure. In the case of a nonagon (figure 5b), nine isosceles triangles are created. From its previous status of regular polygon, we take the value of the central angle to make each angle formed by the lines of the same length in the new isosceles triangles. These triangles then allow the creation of each of the nine bastioned fronts. It is likely that we can use the same reasoning for all the other methods using the centre of regular polygons.

RESULTS
We then managed to have perfect bastioned fronts be it for regular or irregular n-gons and for polygonal chains with minimal user intervention. Thus, only the vertices of the external polygon have to be placed interactively to do the reconstruction of the magistrals.

First, the three possible lines (Pagan, Errard and Vauban) have constraints defined by canonical values. To compare these magistrals to their counterparts

**Figure 6**
Reconstruction according to canonical values for the plan-relief of Toul

**Figure 7**
The magistral (A) is adjusted according to the theoretical parameters (B)
used in the four plans-reliefs, we calculate the average distance between all the respective points of both lines (original and reconstructed). While it was already visually obvious, this first comparative index shows that Vauban’s method was likely to have been chosen for the bastioned fronts of Toul. (figure 6).

However, some adjustments are still necessary to match the original magistral. The values of the theoretical parameters of this line must be adjusted to get closer to the fortifications of the plan-relief. These values are limited according to a range defined by the engineer’s system. In Vauban’s method, the three hierarchical parameters do not deal directly with the entities of the magistral (flanks, faces and curtains) or their properties (angles and lengths); that is why adjustments to the magistral are difficult to realise (figure 7).

This first set of adjustment parameters is often not enough to get an accurate 3D replica. We still have to move some of the magistral’s vertices. But it is done at the expense of the theory and, what is worse, it can conflict with the engineer’s maximes.

Besides these parameter difficulties, adjustments cannot be perfect because they are actually done thanks to the 2D plans that have been used by the original model makers to create the scale model. Even if we noticed that these plans may differ from the plans-reliefs, their use is essential since they allow us to change the values of the adjustment parameters to get closer to the original scale-model. They remain among the closest documents to the original scale model, the rest being treatises and surveys of the damaged scale model (image-based and scan).

**CONCLUSION AND FUTURE WORKS**

In this paper, we have presented an automatic reconstruction of the bastioned fortifications present on the surface of a large collection of centuries-old scale models. Our method is intended to fill in the gap in the digitising data by the creation of parametric components established on the basis of historical documents. These components are then adjusted thanks to several referenced data sources in order to match the fortifications of the plans-reliefs.

Improving the reconstruction process can be done along several lines. First of all, it appears that more than one system can exist side by side in a
single plan-relief or, be layered over a part of a preceding system, which seems to be the case in the scale models of Metz and Verdun. The study of the history of the fortified places, which was already underway, has to be pursued in order to reduce the amount of possible methods.

Then, it is necessary to question the relevance of the current adjustment parameters when they are neither convenient nor satisfactory. Only an in-depth knowledge of the engineer’s techniques will allow us to be consistent with their maximes and to be able to transcribe them into parameters. Moreover, this question cannot be answered without addressing the related issue of the nature of the data upon which the adjustments are realised.

As is summarised in figure 8, we have different sources which have made possible the creation of the scale model and one source which is drawn from it. The treatises are the main vehicles for transmitting theoretical knowledge required for the construction of fortified places. In turn, they have been widely studied in order to realise the plans used by the makers of plans-reliefs. From the 19th century scale models, only damaged plans-reliefs have survived. Thus, at each step, information is lost due to the inherent limitations of each medium. The further our reference data sources are from the original scale model the less accurate the reconstructed model will be. Although we have to deal with the data sources own imperfections (Bae 2002), relevant and systematic points cloud from photogrammetry and laser scanning acquired from the damaged scale model can reduce the amount of uncertainties, especially if they are cross-checked with other references like the 2D plans.

Finally, confronting survey data with the theoretical and parametrical models can be a beneficial because it allows us to chart the evolution of fortifications and the change between representations (Schinko, et al., 2010). Given the purpose of the 3D model of the plans-reliefs, this information can be a useful addition to a semantic model in term of urbanism and fortification evolution.

Even if we are at the beginning of the fortification modelling experiment, the results of the tests conducted are already numerous. We have already tried to pursue the fortification construction inside and outside the magistral outline with satisfactory results (figure 9).

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