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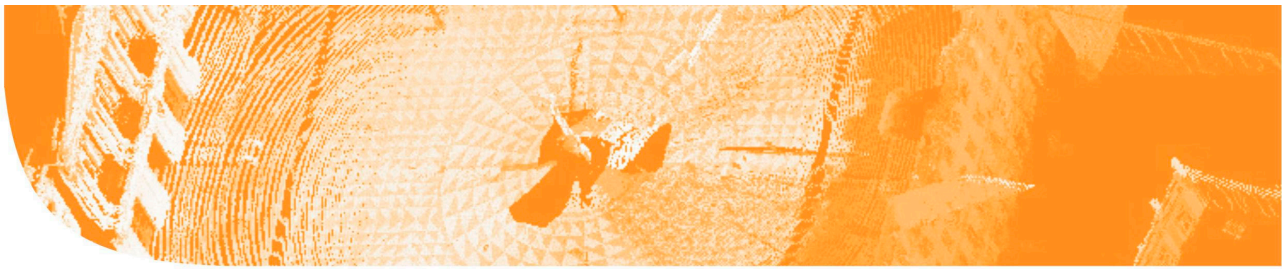
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ARCHITECTURAL MODELING AND ARCHAEOLOGICAL RECONSTITUTION : DIGITAL TOOLS FOR 3D ACQUISITION AND MODELING ASSISTANCE

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KEY WORDS: Architecture, Data Acquisition, Laser Scanner, Remote Sensing, 3D Modeling, CAD

ABSTRACT:

The MAP-CRAI laboratory leads researches dedicated to 3D acquisition procedures (Mensi's "Soisic" laser scanner) and especially to processing the resulting data. The scanner allows the measurement of buildings or architectural details and their restitution based on processing of points clouds data files. To process the data, we chose architectural geometric modeling in order to obtain relevant 3D models, the intended use being architectural representation. Architectural modeling is understood here like a "meta" level compared to geometric modeling. This three-dimensional modeling thus forms a language whose vocabulary would consist of geometrical primitives and whose grammar would consist of specific combinatorial rules. To validate this process, it has been necessary to resort to several experimentations. We thus tested the tools developed for the modeling of a classical 17th century building and its environment. These tools were based here on the morphological characteristics of classical architecture: repetition by translatory movement, symmetry, rotation, hierarchical organization based on the architectural orders, etc... Finally, the 3D model was completed in the modeling software by additional data, such as the textures, obtained on site by photogrammetric measurement. In the archaeological domain, experimentations validating the data acquisition and the 3D modeling chain have already been carried out on a Gallo-Roman temple and are currently being continued on architectural elements related to Khmer civilization (Cambodia). Another experimentation's aspect is the integration of the resulting algorithms in a professional 3D modeling software. These researches aim to facilitate the transition from the acquisition and semantic description step, to a specific geometric modeling known as "architectural modeling" ie: a digital representation form of three-dimensional data completed and adapted to the measured elements.

RESUME : MODELISATION ARCHITECTURALE ET RESTITUTION ARCHEOLOGIQUE : DES OUTILS NUMERIQUES D'ACQUISITION ET D'AIDE A LA MODELISATION 3D.

Le laboratoire MAP-CRAI mène des recherches consacrées à la mise en œuvre de procédures d'acquisition 3D (scanner laser Soisic de Mensi) mais surtout au traitement des données ainsi obtenues. Le scanner permet le relevé de bâtiments ou de détails d'architecture et leur restitution sous forme de fichiers bruts de nuages de points. Pour leur traitement, nous avons retenu la modélisation géométrique architecturale afin d'obtenir des modèles 3D pertinents pour un usage destiné à la représentation architecturale. La modélisation architecturale est comprise ici comme un « méta-niveau » par rapport à la modélisation géométrique. Cette modélisation tridimensionnelle forme ainsi un langage dont le vocabulaire serait constitué de primitives géométriques et la grammaire de règles combinatoires spécifiques. La validation de cette démarche supposait le recours à diverses expérimentations. Nous avons ainsi testé les outils développés pour la modélisation d'un édifice classique du XVIIème et de son environnement. Les outils se fondaient ici sur les caractéristiques morphologiques de l'architecture classique : répétition par translation, symétrie, rotation, organisation hiérarchique basée sur les ordres architecturaux, etc.... Enfin, la modélisation fut complétée dans un modèleur par des données supplémentaires, telles que les textures, obtenues sur place lors d'un relevé photogrammétrique. Dans le domaine de l'archéologie, des expérimentations validant la chaîne d'acquisition et de modélisation 3D ont déjà été menées sur un temple gallo-romain et sont poursuivies actuellement sur des éléments architecturaux liés à la civilisation khmère (Cambodge). Un autre aspect

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des expérimentations réside dans l'intégration des algorithmes développés dans un logiciel de modélisation professionnel. La finalité de ces recherches consiste à faciliter le passage de l'étape d'acquisition et de la description sémantique à une modélisation géométrique spécifique dite «modélisation architecturale», c'est-à-dire sous une forme de représentation numérique de l'information tridimensionnelle complète et adaptée aux éléments relevés.

1. INTRODUCTION

The developments in the acquisition technologies lead to precise three-dimensional measurements being extremely reliable and fast. These possibilities created a demand for digital 3D models based upon these measurements. Archaeology and architecture by nature do not escape this development and require a great number of 3D models and specific modeling, we will call architectural modeling. This article presents the research carried out by the MAP-CRAI laboratory aiming at developing digital tools to aid architectural modeling. After a presentation of the concepts related to a set of themes, architectural modeling, we will present a particular field of application of 3D digital acquisition, i.e. the 3D laser scanner with active triangulation used at the MAP-CRAI laboratory. Then we will expose the experiments combining theoretical research and its implementation in concrete cases.

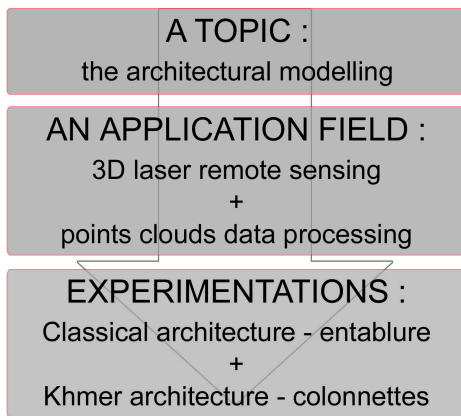


Figure 1. The article principle

2. MODELISATIONS

In this introductory part, we will locate the sets of themes related to the concept of modeling and its corollaries, to reach a better understanding of architectural modeling.

2.1 Model Concept and Data-Processing Modeling

The model concept preserves all its characteristics, no matter what developments are used on the various processes of modeling. If we look at the encyclopaedic definition, a model is defined as: “the object reduced and easy to handle which produces in itself in a simplified form [...] the proportions of a large-sized object, whether it is an architecture or a mechanical device. The reduced object can be subjected to measurements, calculations, physical tests which are not applied conveniently to the produced object. [...] The concept of model is associated with an idea of systematic simplification”. (Universalis, 1995)

The model thus takes properties and characteristic of the original object according to its destination. In the fields of

architecture and archaeology, it is generally defined as a representation of an object in volume in a given scale. The architectural representation must thus be adapted to an objective determines the choice of the method, procedures and tools to be used.

The availability of powerful data-processing tools placed at the disposal of the users the representation tools necessary for computer-aided design and manufacturing. The modeling software thus followed a constant evolution: a very mathematical representation of reality in the form of wire-frame were replaced by boundary representation and voluminal models to reach photo-realistic image synthesis.

Progress observed should not make us forget the most important point of the process of modeling, namely that it depends entirely on the destination of the model to produce.

2.2 Architectural Modeling

We will here briefly present the principal modeling types we can find in the archaeology and architecture fields. The production of a model is subjected to a succession of interdependent steps: data acquisition, data processing and model construction. This process does not change but its formalization varies: there are three principal modeling types: reconstitution, model “as built” and model “as seized”.

2.2.1 The restitution 3D model: In the archaeology field, a 3D model is often used to represent reconstitutions of vestiges based upon fragments. In this case, a model worked out from the measurements is completed by the knowledge and the expertise of specialists in the field (archaeologists, architects, etc.). They validate all the assumptions suggested during modeling time to lead to the completion of the model: a reconstitution.

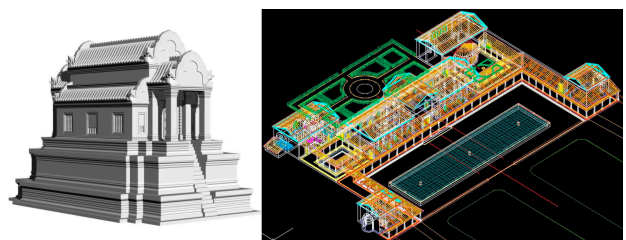


Figure 2. Archaeological restitution examples the library n°54 of Bayon and the Echternach villa (MAP-CRAI & SSMNL).

2.2.2 The "as seized" 3D Model: That means the modeling closest to the measured object, whose relevance is the sole result of measurements quality and the model process development. It represents the construction of an object as it exists. Information necessary to its construction results only from the measurement of the object itself.

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2.2.3 The "as built" 3D Model: It is carried out on the basis of measurements taken on the object without any extrapolation. In archaeology, this modeling is used to mask the effects of the erosion of the stone and the minor defects due to time. Used in an industrial context, this type of modeling also allows the redeployment of installations (revamping) by reconstituting the real state of the building. The modeling built on the basis of measurements considered to be necessary represents a geometrically ideal reality.

There are various methods to carry out these modeling based upon points clouds. We will consider geometrical modeling because the automatic meshing solution, very specific, is discussed further. Geometrical modeling is done according to various methods, often complementary:

2.2.4 Modeling based upon geometrical primitives: This method is based on the work of the operator and a series of geometrical primitives (point, segment, curve, boxes, cylinder, etc.). It is the principle used by the Mensi 3D IPSOS software. This method can take a large amount of time when the modeled object is complex.

2.2.5 Modeling by automatic recognition and reconstitution: based on differential geometry tools that allow the automatic segmentation of points clouds (Goulette, 1999). This method is used in reverse engineering. Although fast because of its automation, the method is generally unsuited to the architectural objects.

2.2.6 Modeling based upon parametric “business” libraries: Used by 3D IPSOS, this development logic may seem interesting, however the existing libraries do not offer the primitives or the architectural objects necessary for architecture modeling.

The processing tools already available appear often insufficient when confronted to the specificity of these models. The study of the modeling processes should allow their development or their optimization. In architectural modeling, various development perspectives have already been considered. One can quote the PAROS project of the GAMSAU which proposes an object-oriented approach of modeling and thus the development of elementary architectural entities.

Based on the treaties of architecture, the GAMSAU develops a library of customizable objects to facilitate architectural modeling (Brakchi, 1997). At the Montreal school of architecture, Hassoun Karam proposes an application based on a deep knowledge of the geometrical rules of design to model an Egyptian column (Karam, 1999). We now will discuss the experimental aspect of the 3D laser scanner acquisition and architectural modeling processes.

3. MEASUREMENT WITH 3D LASER SCANNER AND TREATMENT OF POINTS CLOUDS

There are many concurrent and sometimes complementary techniques in the buildings measurement field, such as photogrammetry for instance. We here will concentrate on only one device of three-dimensional data acquisition which will be carried out at the time of the experiments presented further.

3.1 Data Acquisition

3.1.1 The technology, the various methods: In the field of 3D laser scanners, there are two techniques of acquisition resting on different principles: the laser triangulation planes whose operation will be detailed here; and laser telemetry. Laser telemetry consists in measuring the time taken by a ray of light to reach the measured object. It is a fast acquisition technique. The measuring devices are also associated with a mechanical system that allows the sweeping of the measured scene. These measuring technologies depend on the laws of optics: the hidden parts or shade zones necessitate several shots around the object being measured (Goulette, 1999).

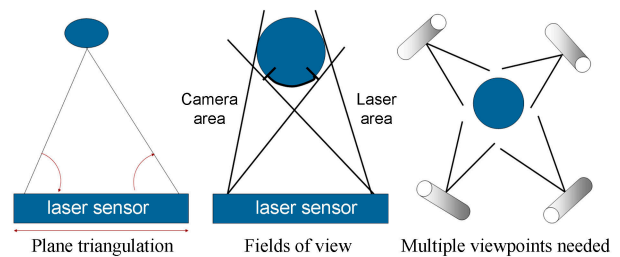


Figure 3. Laser scanner acquisition principles

3.1.2 The SOISIC triangulation sensor:

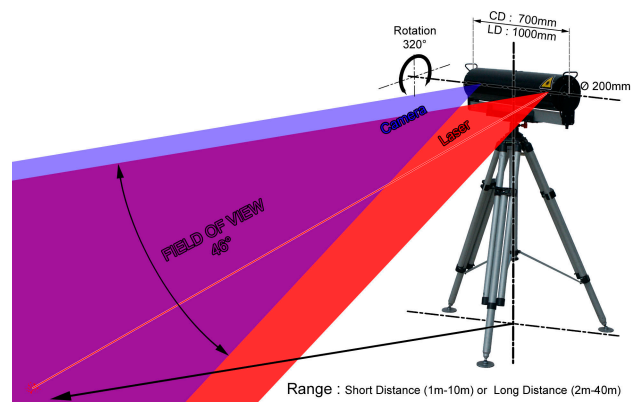


Figure 4. The MENSİ “SOISIC” 3D laser scanner

The “SOISIC” scanner is based upon the principle of acquisition by plane laser triangulation. The sensor uses a laser beam guided by a mobile mirror. The image of the point emitted by the laser scanner on the measured object is captured by a CCD (coupled charged device) video camera: coordinates X, Y and Z are thus determined by trigonometry. The scanner is an active measuring device and therefore does not require any additional external lighting. The optimal use of the device is in a low ambient light: the measurements taken outside are thus done preferably in low light intensity (Boehler, 2001) Driven by a PC, the sensor can collect the 3D coordinates of the laser spot at the rate of about 100 points/second (MENSİ S series). Depending on the sensor model, the field depth varies from 1 to 60 meters (approx.). The measuring accuracy is 1mm at a distance of 5 meters. The SOISIC Scanner is available in two versions: Long distance (range varying from 5 to 40 meters) and

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Short distance (range varying from 0.8 to 15 meters). The operator defines the collecting surface and the sweeping density depending on the measured object. Measurements are stored in files, each "point of view" of an object being composed of the sub-points of view corresponding to the reference spheres and to the various shots executed on this object. The scanner position compared to the object, the points' capture precision and the complementarity of the points of view are thus as many factors which contribute to a better exploitation of the data obtained. The resulting files are then transferred on the workstation where the data processing is carried out. The measurement device is then completed with a consolidation and modeling software (3DIPSOS).

3.2 Data Processing

The points cloud is the three-dimensional set of the points measured by the sensor on the surface of the object, each point being known at least by its 3D coordinates (x, y, z). Each cloud of points will correspond to a point of view and not to a logical cutting out of the object. It is thus necessary to process these raw data in order to facilitate its exploitation.

3.2.1 Consolidation: The first step consists in "consolidating" ("strengthening") the points clouds, i.e. gathering all sub points of view in a global Cartesian reference mark. Reference spheres placed judiciously around the measured object during the acquisition phase allow to save a important amount of time. Indeed, a minimum of three reference spheres compose a reference mark for each sub-point of view, and if each shot has a reference mark common to another shot, a total reorganization of the points clouds is possible in a semiautomatic way. After control, the points clouds can be merged in one unique big set.

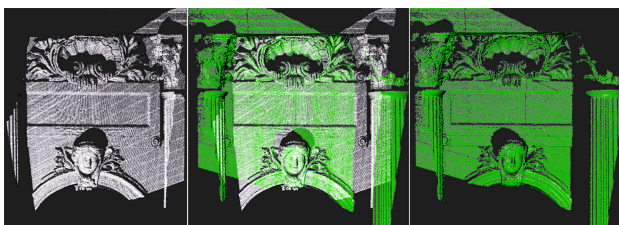
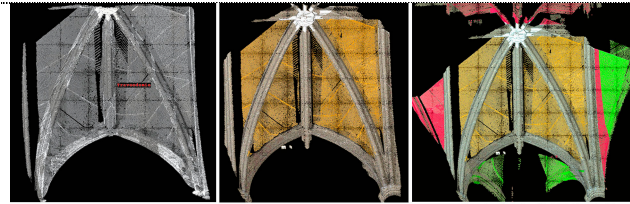


Figure 5. Consolidation (detail of the water tower)

3.2.2 Segmentation: Segmenting a points cloud consists in constituting logical subsets. This is carried out by isolating sets of points corresponding to parts of the object or of the environment. The segmentation is carried out manually: the operator selects subset of points in order to gather them. Resulting subsets, that will form lists of points, are ordered in a hierarchical table. The segmented cloud of points could not be exploited as it is, because the unchanged volume of data limits handling: this step allows the hierarchically arranged export of geometrically referred data. This is a prerequisite before processing the data in a third-party software.



Capitol hall (FIGEAC)

Figure 6. Three stages of segmentation : Left, the original consolidated points cloud, right: the result after treatment, where the veins are isolated from the remainder of the vault

3.2.3 Meshing: The 3DIPSOS software has tools for meshing construction (also called polygonisation). These tools rely on algorithms which build facets between the points by triangulation and calculations of least squares approximation. Thus a surface replaces a set of points, it is however necessary to optimize it in order to remove the possible and undesirable artefacts. This treatment of points cloud is adapted to the objects which have complex morphologies: statues, decorative details. The mathematical optimization of these meshes allows to considerably decrease the data amount, at the expense of information and precision.

4. DEVELOPING TOOLS TO ASSIST MODELING BASED UPON CLOUDS OF POINTS

One of the first experiments employing the 3D laser scanner and the process of modeling, carried out by the MAP CRAI laboratory, was the archaeological reconstitution of a Gallo-Roman temple of Nasium (Bur, 2003). This work allowed us to do the initial validation of the 3D digitalization and modeling process, in an archaeological reconstitution context. During this experimentation, it appeared that the laser scanner acquisition technique was adapted to this type of project, but the modeling process proved much slower. It thus appeared to us judicious to direct research towards the architectural modeling field. We will present here two complementary experiments which have enabled us to progress in this field: the first dedicated to a detail of classical architecture, the second to Khmer architecture. They follow a similar methodology: on the one hand an analytical study of the objects in order to formalize tools to aid modeling, on the other hand a 3D laser scanner measurement work in order to reach a concrete application.

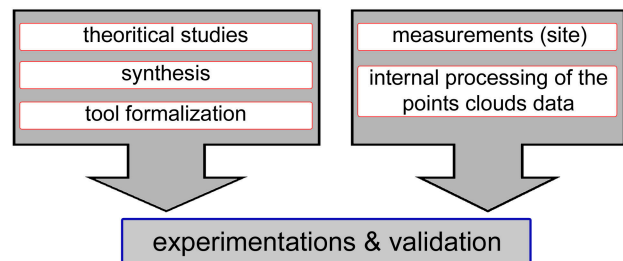


Figure 7. Proposal for a global methodology

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4.1 Classical Architecture Modeling : Theoretical Study And Experimentation

4.1.1 Theoretical Study - Classical architecture: The classical architectural style is one of the most widespread styles in the history of architecture. Classical architecture, controlled by rules of harmony and suitability, has been described by various architecture treatises (Palladio 1980), (Vitruves, 1979). The architectonic orders of this style fall in five main categories: the Doric order, the Ionic order, the Corinthian order, the Tuscan order and the composite order. The latter, developed originally by the Romans, based upon the preceding orders, has spread very largely. This study is therefore more particularly directed towards this particular order. In addition, the Tuscan order intrinsic nature allows us to assume an extrapolation of the modeling method to all the orders. At the MAP-CRAI laboratory, Reda Begriche (Begriche, 2003) developed geometrical tools based on the knowledge of this architectural order specificities. After a synthetic view of the treatises of architectonic composition of the classical period, his proposal is concretized with tools aiming at optimizing the production of 3D models based upon points clouds, and has been focused more precisely on classical entablature.

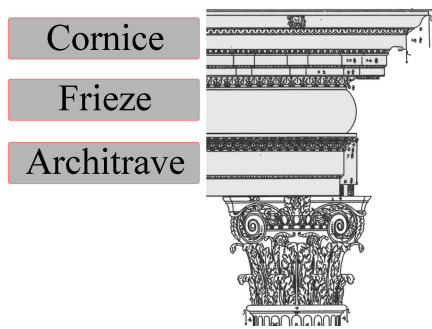


Figure 8 . entablature according to Palladio

Laying on the columns capitals, the entablature is composed of the architrave, frieze and cornice.

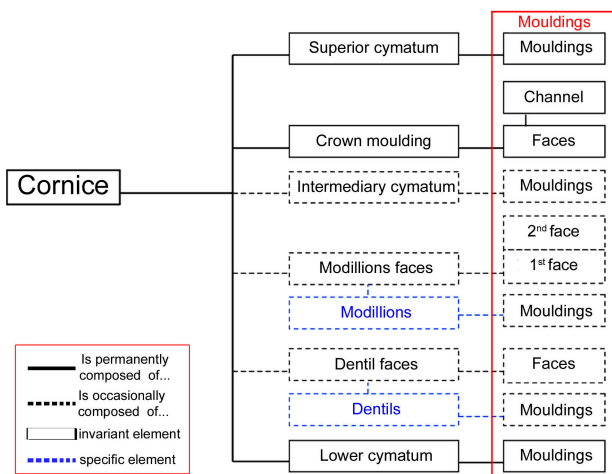


Figure 9 : cornice breakdown diagram (Begriche, 2003)

The synthetic study of the treatises, together with the breakdown of the composite entablature, allow to lead to an elementary architectonic primitive: the moulding. The cornice example lets us apprehend the breakdown logic which leads to it.

An elementary classification of all mouldings based upon their geometrical characteristics is obtained thanks to a systematic analysis work of each type of moulding.

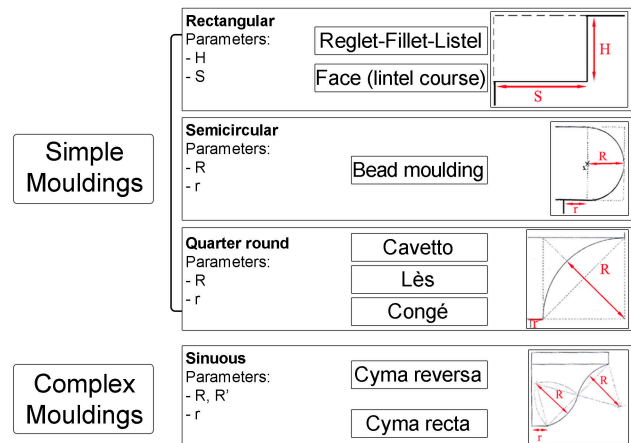


Figure 10. the mouldings classification according to their geometrical characteristics (Begriche, 2003)

The synthesis of the theoretical elements presented previously allows the definition of tools to help modeling. The general principle of these tools is to offer the possibility to adapt a modeling of parameterized mouldings to a points cloud. The modeling of the complete entablature according to this principle combines a constant profile body with specific elements. The constant body profile is carried out by an extrusion, i.e. a linear translation, of a mouldings combination. Specific elements (dentils, modillions) are generated according to the same principle then reproduced in networks if necessary. Algorithms programmed in LISP language made it possible to integrate the various adaptable mouldings in a CAD software, Autocad (by Autodesk). These mouldings allow a “guided modeling”: the anchor points of the geometrical primitives which compose the mouldings are adjusted on the points cloud resulting from the 3D laser scanner measurement.

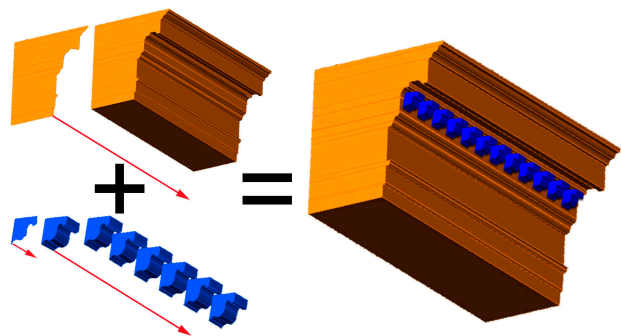


Figure 11. Profile extrusion and specific elements.

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4.1.2 Modeling experimentation: The Peyrou water tower

□ Context, modeling of the Peyrou esplanade:

The town of Montpellier wished to carry out a photo-realistic 3D visualization of the Peyrou esplanade and its water tower, within the larger project of a global 3D modeling of the city. This modeling's goal is to illustrate a digital map of the city, aimed at tourists. This survey and this modeling were an opportunity to allow collaboration of two research teams with the town of Montpellier services, on a work with multiple objectives. The two teams are part of the UMR 694 MAP: the CRAI and the PAGE. Competences of the two laboratories in the acquisition field are complementary: the CRAI team (J-P. Perrin, V. Marchal and A. Fuchs) being in charge of the 3D laser scanner measurement, while the PAGE team (P. Grussenmeyer, S. Guillemin, E. Alby) handled the photogrammetric and topographic measurements. The data processing also has been carried out according to respective competences of each laboratory.

The aims of this acquisition and modeling campaign were multiple: initially the objective was to provide an exploitable 3D digital model, but it was also the opportunity to confront the various acquisition techniques and to study their complementarities. The aspect which interests us particularly here, is the experimental approach of the 3D laser scanner acquisition processes and the Peyrou tower modeling using the tools developed at the CRAI. This project should allow to validate in a concrete context these 3D modeling aid tools.

□ Historical and geographical context:

The Peyrou esplanade in Montpellier is an urban space where we can find several remarkable elements of various natures: an urban walk, an equestrian statue of Louis XIV, a triumphal arch, an aqueduct as well as a water tower. Although these elements of multiple forms and heterogeneous natures constitute a coherent urban whole, we will here focus more particularly on the latter, that will be measured with the 3D laser scanner.



Figure 12. The Peyrou water tower, Montpellier.

The Peyrou esplanade, the Louis XIV statue and the triumphal arch:

The installation of the Peyrou esplanade as well as the triumphal arch construction took place at the end of the XVIIIth century. The installation of an equestrian statue of Louis XIV confirmed the strength of the royal power on the city in 1718. This urban unit, decorated in its lower part with ponds and

flower beds, currently serves as a pleasant walk for the inhabitants of Montpellier.

The St Clement aqueduct and the Peyrou water tower:

The St Clement aqueduct has been built during the second half of the XVIIIth century. 880 meters long, it consists of 236 stone arches made up in two series superimposed on a model close to the Gard bridge. At its end, a water tank surmounted of a decorative temple allowed to supply the town of Montpellier with water. The monumental architectural treatment of the temple with columns based on a hexagonal level is completed with circular staircases and a decorative pond.

These buildings and particularly the water tower present a classical architecture. The dimensions and the morphology of the water tower make it an ideal experimentation subject for 3D laser scanner measurement and application of our 3D modeling aid tools.

□ Experimental results, employed tools and points cloud:

Although the exhaustive description and the comparison of the various acquisition techniques employed (photogrammetry, 3D laser scanner measurement) was one of the fundamental aspects of this study (Fuchs, 2004). However we will here exclusively concentrate on the techniques related to 3D laser scanner and treatment of the resulting points clouds.

3D laser acquisition:

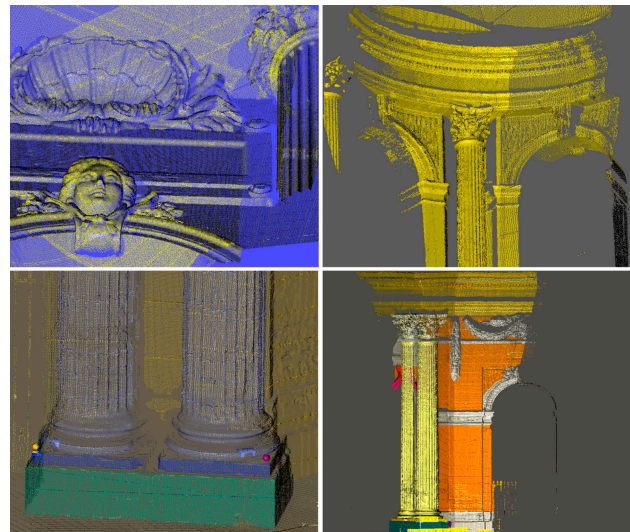


Figure 13. Points clouds resulting from 3D laser survey of the Peyrou water tower

The measurement with the 3D laser scanner of the Peyrou water tower proceeded in several phases, spread over four days. The study of the building morphology clearly emphasized its symmetrical composition: i.e. a plan with hexagonal basis. The measurement thus focused on 1/6th of the building which will make it possible to recompose it in its whole. We thus carried out several series of external measurements on the entire building. Those were completed with interior measurements as well as measurement of a decorative detail. After a measurement test done during the day which proved to be disappointing in

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terms of results, all the measurements have been carried out at night. This is most certainly due to the important diurnal luminosity at this period of the year (June) in the south of France. The precision of the external and interior measurements has been defined in order to be lower than 2mm on the measured object. This appears entirely sufficient for a modeling on the building scale. The measurements of the detail have been carried out with a precision lower than the millimeter. All the measurements thus allowed us to reach a total of approximately 2 million points.

Processing of the collected data:

All the collected data has then been treated according to the traditional consolidation and segmentation process of the 3D laser scanner specific software (Mensi 3D IPSOS). This treatment allowed to initially obtain a global model of 3D points cloud then to gradually export the various points sub-groups while doing the geometrical and architectural modeling of the building. To continue the experimental approach, we then built a geometrical model based upon these measurements. This type of modeling is particularly well suited because of the morphology of the building (symmetries, repetitive architectural elements). We would like to highlight here that we dealt with geometrical modeling when the modeling relies on traditional modeling tools based upon geometrical primitives, while we will call architectural modeling the modeling that employs the specific tools that we developed. The photographs taken during the photogrammetric survey also brought additional information, essential to facilitate modeling since there were various “shade zones” in the laser measurement, because of the high situation of the cornice in particular. These pictures also allowed to visually validate the relevance of the resulting model.

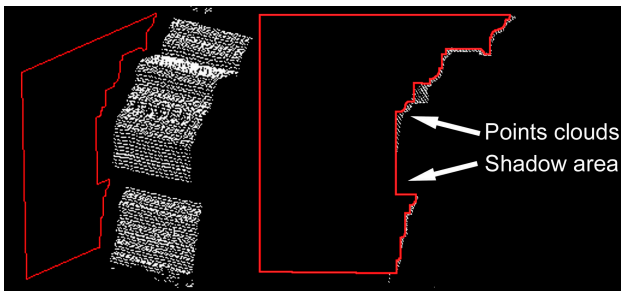


Figure 14. Profile modeled upon the points cloud.



Figure 15. Photography and 3D model of the water tower (VRML).

The modeling of the building has been carried out gradually in CAD software (Autocad), modeled elements being referred in a global Cartesian reference mark. The architectural modeling

tools developed at the CRAI were employed to carry out the modeling of all the cornice. The other parts of the buildings were modeled in a more conventional way but by keeping in mind the wish to extend the architectural modeling tools: the various steps of modeling have systematically been broken up and the result compared with the architectural treatises. In the case presented on the following figure, the geometrical 3D model obtained with the points clouds proved to be extremely close to the architectural theory.

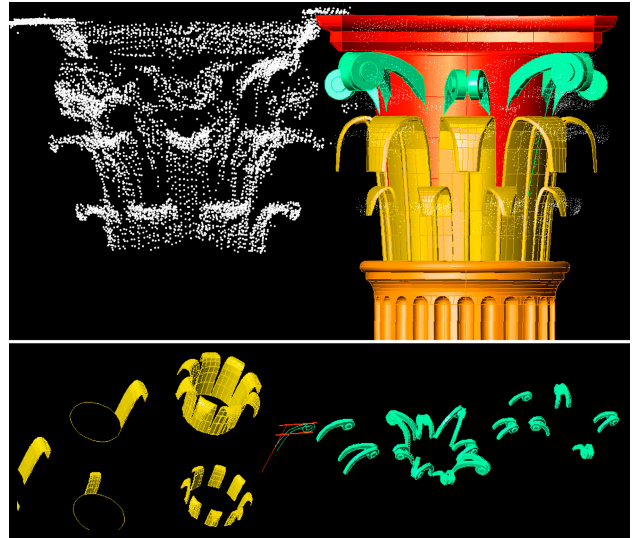


Figure 16. Process of capital modeling and points cloud.

To conclude this experimentation, it appears that the 3D models obtained by associating the developed tools with the measurements prove completely satisfactory in terms of precision. The architectural primitives allowed a considerably accelerated modeling and especially more relevant. Indeed these primitives formalized upon the synthesis of theoretical architectural knowledge, could guide in a completely meaningful way the operator when he faced “shade zones” on the measurement. Of course the initial step of tools formalization can be regarded as relatively long, but the developed tools are reusable and, we saw it with this experimentation, are adapted to the modeling of classical architecture based upon points clouds. The elements of decorations such as the various sculptures or the decorative details (acanthus leaf of the capital) are of course excluded from this type of modeling: the meshing by automatic triangulation gives more adapted especially faster results.

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4.2 Khmer Architecture Modeling: Extension of the Method on a New Field of Study

4.2.1 Theoretical Study, The Khmer Architecture: The Khmer civilization developed from the 7th century, also called pre-angkorian period, to the middle of the 13th century in a geographical area currently occupied by Kampuchea. The Khmer people managed to develop an homogeneous civilization mainly based on Indian and Chinese influences, but also on Javanese influences. Technical progress in agriculture, such as the angkorian irrigation, which made it possible to control the monsoons thanks to the construction of immense water tanks (“barays”), constitute the starting point of the spectacular development of this civilization (Sterling, 1970). The Khmer sovereigns knew how to use the resources released from the agricultural work, as well as a strict and centralized social organization, to develop an extremely rich urban and architectural movement. All those elements permitted the Khmer civilization to devote a great part of its energy to the construction of monumental buildings. The main monuments, built out of stone many centuries ago, still exist: they therefore became the object of archaeological and architectural study. Moreover, the archaeological studies clearly established that this stone architecture was inspired by wooden architecture; the choice of a stronger material can be explained by the primarily cultural vocation of the buildings. The Khmer architectural language is governed by a set of correspondences and spiritual representations that have a specific vocabulary and syntax. The concepts of symmetry, axiality and repetition constitute the major morphological characteristic of this architecture. Symmetry, axiality and repetition are to be found as well on the outline level of the monuments as on details of the Khmer architecture, what interests us more particularly in this study.

□ Exploratory study of the colonnettes:

Classification, synthesis, hierarchisation:

The column constitutes an architectonic entity common to almost every types of architecture (Classical, Egyptian, Arabo-Muslim architecture). The column is an element that has been studied in architecture as well as in archaeology. This experimentation aims to continue the previous analysis, but more specifically on the colonnettes which decorate the Khmer monuments.

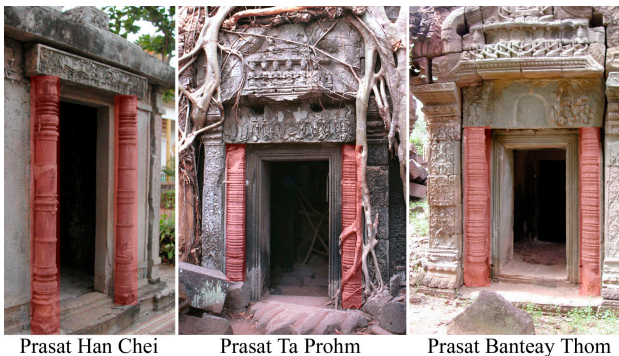


Figure 17. Various colonnettes of Khmer buildings (pictures: O. Cunin).

From a morphological point of view, the colonnettes show the same characteristics as a column. However, their role in the building is different: colonnettes are intended to support the decorative lintel of the openings. Thanks to their decorative elements and to the rhythm system of their rings, colonnettes contributed to update the stylistic development of the Khmer architecture. The study of various descriptive texts and available graphic elements allowed us to establish a preliminary classification of the colonnettes. The synthesis of Henri Marchal and Henri Parmentier’s work published by Jean Boisselier (Boisselier, 1966) was used as a reference for this classification. The photographs carried out by Olivier Cunin (Cunin, 2004) during his archaeological studies of various sites completed the information available. The next step was to establish a hierarchisation of the preliminary classification. This hierarchisation was made on the basis of the elevations and characteristics of the colonnette’s sections.

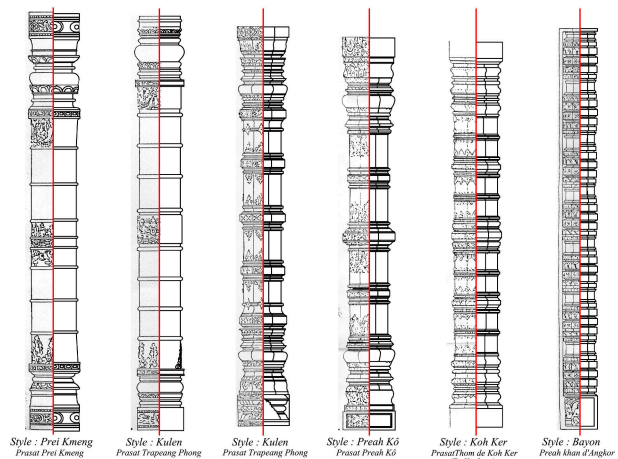


Figure 18. Stylistic classification and CAD models

As soon as the global hierarchisation was completed, a detailed decomposition of six defined colonnettes was carried out in order to identify their morphological characteristics. The styles which we studied were, by chronological order: the Prei Kmeng style (636-656), the Kulen style (802-877), the Preah Ko style (877-889), the Koh Ker style (921-941) and finally, the Bayon style (881-1219). In general, the pre-angkorian period presents a cylindrical form, heritage of the Indian art, whereas the style of Angkor presents a barrel of polygonal section with carved base. From a stylistic point of view, the intermediate period known as Banteay Srei (967-1000) is considered as the richest period. On a strictly morphological point of view, it is noticeable that the oldest colonnettes (Prei Kmeng style) are all based on an horizontal symmetry, based on a central reglet. This reglet gradually evolved and became the more complex shape of central ring. In the later styles, this central ring will be supplemented by secondary rings. Starting from this original axiality, the decoration of the colonnettes’ barrels resembles a composition and repetition of those rings. The later styles (Angkor) present barrels with carved base. The shape of the barrels, cylindrical at the beginning, progressively became orthogonal. This orthogonal form is based on figure 4, synonym of perfection in Indian cosmology (Sterling, 1970). The colonnettes with cylindrical

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barrels, just like the colonnettes with octagonal barrels, also present a symmetry based on the vertical axis.

Development of the architectural model:

Once the global work of synthesis and hierarchisation is completed on the colonnette's level, the following step consists in working out an architectural model of the colonnette itself. This operation consists in a breakdown of the architectural object by a search for repetitive elements in generic entities that can be isolated and that are able to produce particular objects (by filiations). As soon as the components of the colonnette are identified, they are broken up into under several elements.

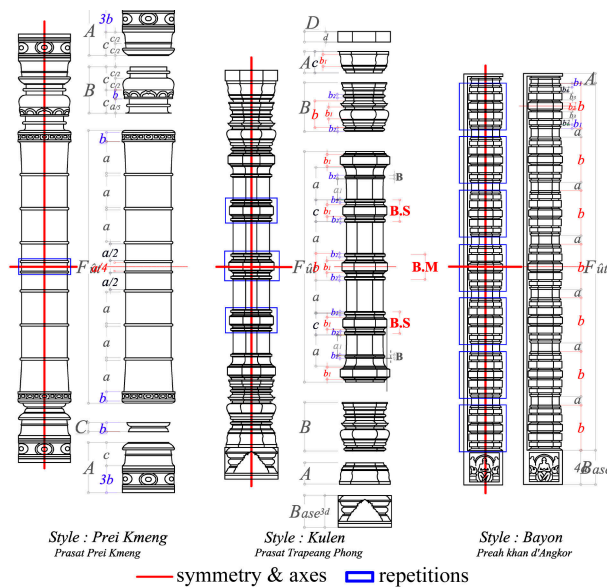


Figure 19. Hierarchisation and colonnette analysis

The detailed morphological analysis of the elements which compose the colonnettes reveals a constant logic of symmetry and proportion. It is important to underline one of the rings' characteristic: identical elements are indeed to be found between various styles of colonnettes, but the drawings and the proportions of these elements are variable. On the other hand, when only one type of colonnette is studied, the study reveals a noticeable variation on the ring scale factor. Each under element is then analyzed in order to specify its geometrical primitives as well as their parameters (Begrliche, 2003). The work consequently consists in identifying each moulding type and to carry out its breakdown in geometrical primitives. By combining these geometrical primitives between each other, the writing of algorithms then makes it possible to define architectural primitives, which can be considered as the "meta" level of the geometrical level. These algorithms are programmed in LISP language, in order to be interpreted by the CAD software AutoCAD (AUTODESK).

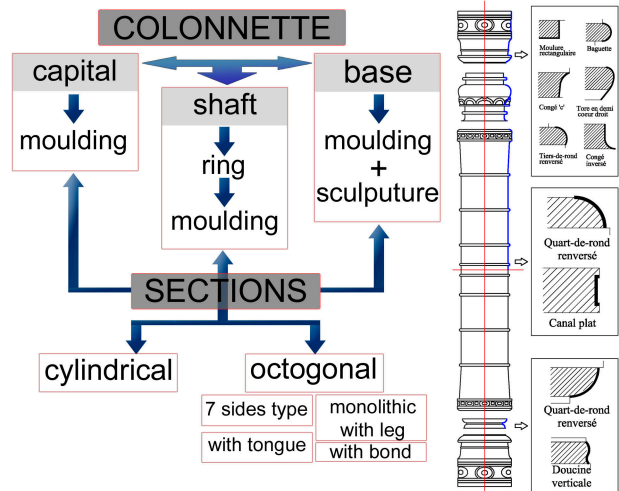


Figure 20. Breakdown of the Prei Kmeng colonnette

Specific decorative elements are added as decorative design. They are also incorporated in the previously defined library of architectural primitives.

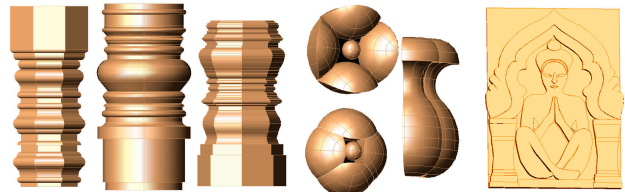


Figure 21. Specific objects library

4.2.2 Experimentation, 3D data acquisition in the Guimet Museum:

□ Initiative and work context:

Within the CRAI laboratory, we did not have suitable material to validate the numerical tools developed to model the Khmer architectural elements. We therefore contacted the Guimet Museum in Paris in order to validate our work by an experimentation based on concrete material, using a 3D laser to acquire points clouds data. The Guimet Museum or "National Museum of Asian Arts" gathers a great number of collections from various countries of South East Asia. Many elements related to Khmer art and architecture can be observed in the collections of the museum. We found architectural details among these elements, colonnettes in particular, which interested us for the most part.

□ The Historical Context:

The colonnettes:

The Guimet Museum owns several colonnettes that come from Khmer temples. We chose to take a complete 3D measurement of two of them. In order to use the maximal number of the tools we defined during our theoretical study, we chose two colonnettes with quite distinct morphological styles. The oldest colonnette we studied belonged to the pre-angkorian style, whereas the second one was built during the Angkor Vat period.

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The Prei Kmeng Temple Colonnade - Prei Kmeng Style (7th Century): It is a colonnette with bare cylindrical barrel and central reglet. From a strictly artistic point of view, this style was developed under a vishnuite iconographic context, which is identified as the oldest phase of Kampuchean brahmanic art. The decoration of the colonnette is composed of pendant bulbs for the capital and the base.

The Phnom Da Temple Colonnade - Angkor Vat Style (12th Century): This colonnette presents an octagonal barrel with central ring. This central ring is supplemented with secondary rings. The stylistic evolution led to the disappearance of the distinction between the base, the barrel and the capital by a continuous repetition of rings. This style can be identified thanks to the iconography located on the basis of the colonnette.



Figure 22. Photographs and points clouds - left the Prei Kmeng style and right the Phnom Da style – Guimet museum, Paris.

□ Experimental Results, Tools used in the Experience and points clouds data:

The 3D Laser Acquisition:

The data acquisition lasted one day and a half. The first half-day was devoted to the installation of the measurement devices and to the launching of a first laser scanner measurement. The second day, which was also the closing day of the museum, was employed with the other laser scans. The conditions of 3D laser scanning were almost ideal : weak surrounding luminosity and few luminous variations. We carried out several shots for each colonnette in order to obtain complete points clouds data for the measured objects, This was not necessary, if we considers the logic of experimentation of our 3D modeling tools : indeed, thanks to the symmetry of the colonnettes, a scanning of some specific parts would have been sufficient to obtain a complete model. However, it appeared interesting for us to take a complete 3D acquisition of the 2 pieces in order to have data for complementary experimentations. The smoothness of the details of these colonnettes enabled us to scan these objects with a precision close to the millimeter. The possibilities of the laser

being of course quite higher in terms of precision than the actual measurement, it was a compromise between the duration of acquisition necessary to each scanning and the time we had to realize them. We nevertheless proceeded to a double measurement of the Angkor Vat style colonnette: namely, we realized a global laser scanning followed by the more detailed measurement of the zones which interested us more particularly, i.e. the rings of the colonnette. By doing those two 3D laser scanning, we obtained near 900000 points.

The collected data processing:

Just like the previous digitalization process, the preliminary treatment of the laser scanning, namely their consolidation and their segmentation, was done with the 3D Ipsos software. Consolidation, i.e. the fusion of all groups of 3D points clouds in the same Cartesian reference mark, was accomplished semi automatically thanks to the installation of spheres as reference marks during data acquisition. Various segmentations were then executed to facilitate the exploitation of the relatively dense data during the modeling. The developed algorithms were then implemented in the CAD software (Autocad Autodesk) in LISP language before the start of the modeling itself. The morphological variations between the two colonnettes led us to the execution of different procedures. For the colonnette of the Prei Kmeng temple, the reconstitution was carried out by the revolution of a total profile, with was built with mouldings. On the other hand, the colonnette of the Phnom Da temple, with octagonal section, was executed by an extraction of the profile of rings, according to an octagonal way. These rings are then repeated on the barrel according to a logic of superposition and repetition. The modeling of the capital and the base is made in a separate way for the barrels of orthogonal section. The specific elements such as the lotus buttons are then added at the end of the modeling.

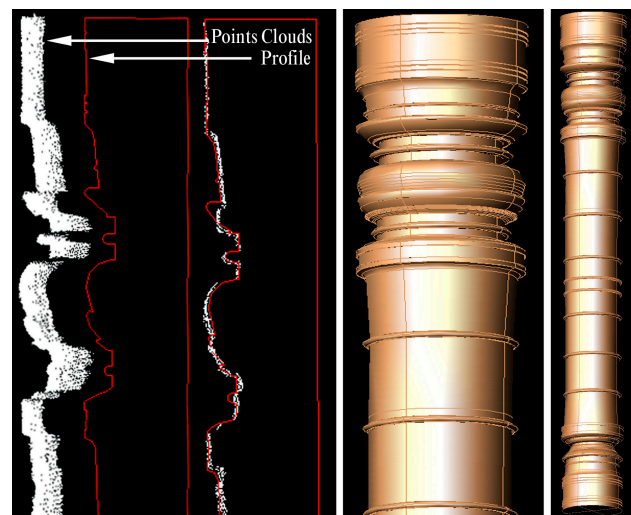


Figure 23 : Prei Kmeng colonnette : from left to right, points cloud, CAD profile and 3D model

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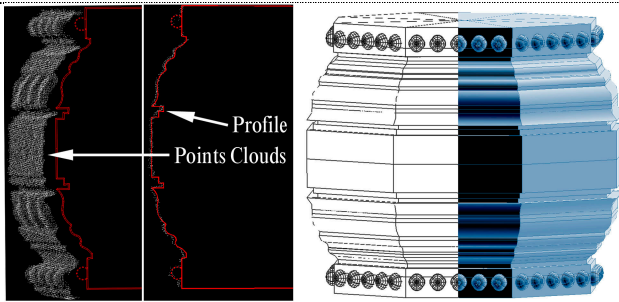


Figure 24 : Phnom Da colonnette, a ring. From left to right, points cloud, CAD profile and 3D model

As shown on figure 25, the developed tools allow a precise modeling, close to the measured object.

This can be explained by the adequacy of the tool to the corpus of modeled forms. Indeed, the theoretical study of different types of colonnettes made it possible to accumulate a sum of knowledge restored in the developed tools. This type of tool is of course intended to model the base form of each colonnette. When we leave the field of forms based on geometrical primitives, it is necessary to consider the solutions suggested by automatic triangulation, used for example in the case of the classical architecture.

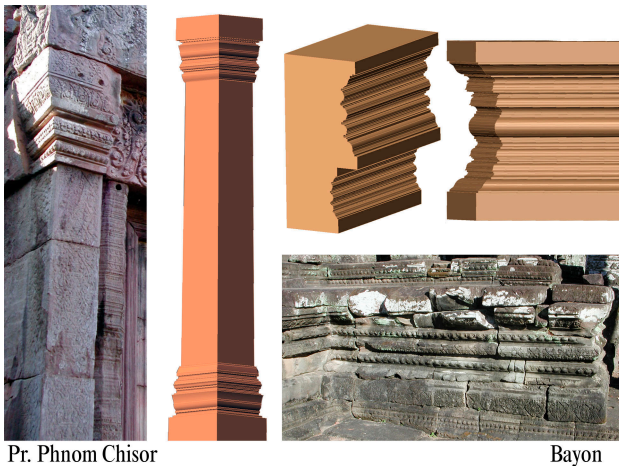


Figure 25. Tests of the tools extended use : 3D models a pilaster and a wall base.

In addition, we find it judicious to develop our research towards other drawing or CAD software. Experimentations carried out with other software reveal a more flexible use potential. Finally, the digitalization of archaeological fragments in numerical form is interesting when those fragments are artefacts undergoing the attack of time and climate. Digitalization executed in the form of points clouds data acquisition constitutes a memory of the object condition at a given time: this can be extremely interesting as far as cultural heritage is concerned.

5. CONCLUSION

The use of modeling tools during various concrete experimentations has already led to the validation of the numerical measure and modeling tools. Architectural modeling

facilitates the precise identification of what is needed from a numerical tool, but also facilitates the test of the developed tools. Thus, future architectural work can consist in the development of additional modeling tools and their implementation in professional modeling software. The question here is to develop appropriate tools to execute a method validated by concrete experimentation.

In addition, the methodology involved during this modeling process facilitates the acquisition of architectural knowledge. Indeed, if one considers architectural primitives (in our case, mouldings) as the vocabulary of an architectural language, the knowledge of the rules which structure it, i.e. its grammar, cannot be carried out without some architectural and archaeological culture.

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