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Gathering, integration, and interpretation of heterogeneous data for the virtual reconstruction of the Notre Dame de Paris roof structure

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Abstract

The objective of this case study is to present the issues, methods and experiments underway to enable the acquisition of data and the creation of digital models of the timber structures, also known as the *Forest*, of Notre-Dame de Paris at different temporal states. Among the different models created, a restitution was developed from all the data collected and produced. This interpretation is the result of collecting, collating, and synthesizing heterogeneous data on pre- and post-fire structures. Indeed, the constitution of this model is also based on new data, obtained after the accident, which required the development of ad-hoc solutions to meet the various constraints of the site. These different resources have made it possible to produce the first univocal and three-dimensional restitution of the frameworks before - and after - the fire and the way to gather in particular all the partial data having been used to create it. This experimentation proposes the necessary qualities to enrich the future ecosystem of analysis and multidimensional memorization for the restoration and conservation of Notre-Dame.

Keywords: 3D reconstruction, Wooden structure, Documentation, Photogrammetry, Camera optimization

1. Introduction

Since its disappearance in the fire of April 2019, the *Forest* of Notre-Dame de Paris (NDP) has been the subject of a great deal of debate among experts and laymen. In the discussions about the feasibility of an identical reconstruction of the roof of NDP, concerns were expressed very early about the age and the quantity of wood necessary to rebuild the destroyed frame, as well as on the knowledge of the carpenters to reproduce multiseccular construction techniques [1]. Data whose reliability is not always established were relayed in the scientific community, while at the same time new studies carried out within the framework of the restoration site were published [2]. However, two constraints have been largely neglected because of presuppositions about the state of the documentation on the cathedral.

On the one hand, the state of documentation and knowledge about the Forest was not established despite the proliferation of images and seductive speeches about the major and possible contribution of pre-existing data, e.g., 3D point clouds and video game assets. However, this was a determining factor to consider a reconstruction of the medieval frames according to an authentic approach [3]. On the other hand, the sparse but reliable existing documentation reminds us that the Forest is the result of eight centuries of reuse, alterations, repairs and modifications that would have to be restored if we were to adhere to the definition of identical [4]. However, until the early 2010s, the frames remain poorly known [5] while reference texts already pointed to the problem of preservation of wooden structures and make the question of record-keeping a foundational issue of documentation and conservation [6]. The studies carried out by the architects Rémi Fromont (today one of the chief architects of historical monuments of the NDP restoration project) and Cédric Trentesaux, during their professional training at the Centre des Hautes Études de Chaillot, France, answer in part to these injunctions.

They established and criticized the extreme heterogeneity of the documentation they inventoried. Their work shows in particular that there is no reliable documentation on the scale of the timber structure as a whole which constitutes this impressive work: 100 meters long, a span of about 13 meters for 10 meters high. Despite the quality of this study and in particular the critical analysis of the ancient documentation, more recent sources of information are not mentioned, in particular several laser surveys carried out between 2010 and 2014, or the numerous photographic reports made over the years in the cathedral's attic. Although they did not want to use digital surveys, the two architects had to rely on a total station to combine geometric precision and completeness of observation to be able to produce the most accurate documents possible [7]. Digital approaches are relevant, if not one of the only solutions, to survey and represent three-dimensional frameworks with extremely dense timber framing configurations [8–10]. Even if remarkable traditional techniques exist to document and visualize framing like the scribing tradition in French timber framing also known as “*trait de charpente*” [11], these tools require a heavy learning curve to master their codes of representation [12], which can hinder at the end the collaboration and the multidisciplinary studies that this heritage requires.

The April 2019 fire broke out just as the NDP spire was entering its renovation phase leaving partial documentation that this project aims to complete. In addition to the existing data that has been systematically collected since the launch of the scientific project, new data have been produced using ad-hoc devices developed to meet the logistical, environmental and spatial constraints of the NDP site. The April 2019 fire significantly challenged traditional survey techniques usable at the construction site, as we had to digitize, identify, and annotate the charred remains of the *Forest* that had been deposited on the *extrados* of the vaults. We were thus led to imagine and develop a system that would allow us to model and integrate the stratigraphy of the debris with “in progress” tools devoted to the visualization, annotation and interpretation of the data already collected.

2. Research aim

This case study focuses on several levels of interdependent objectives that determine the diachronic and morphological study of the NDP's framing.

The first objective is the enrichment of the documentary fund relating to the framing by taking as a starting point the study of Fromont and Trentesaux. It is completed in particular by the creation of new 2D and 3D data representing the different spatiotemporal states of the framing and its constituents since the fire: charred remains on the *extrados*, displaced on the ground of the cathedral, etc. Each of these elements supports linking systematic analyses and new experimental data.

The second objective is to evaluate the degree of completeness of this documentation through the implementation of a virtual reconstruction in its state immediately prior to the incident. This restitution [13,14] takes the form of a 3D model representing the result of 800 years of existence of the framing marked by deformations, repairs, modifications, etc. It is intended to become an unambiguous tool that can evolve according to the production of new knowledge or technological developments.

Taking into account these last points must finally allow to participate to the digital environment of data sharing an unequivocal representation for the diachronic study of the NDP cathedral as a whole.

3. Methods and materials

The fire at the NDP is causing a paradigm shift in the approach to documenting and managing the building's structures. As the only part of the cathedral that almost completely disappeared during the fire, the object of this study requires the implementation of different methodologies for the collection, processing and interpretation of data according to the different states of existence of the structures and

their constituent elements, which have gone from an immobile to mobile preservation. The two methods converge in the form of a diachronic tool, i.e., a digital model of the structures.

The digital restitution of the *Forest* is based on documents produced before the fire, but also after the accident. These information sources are of a great variety in their nature (iconographic, 3D, textual, etc.), reliability, disciplinary origin, etc. The collection of this widely scattered documentation is still in progress. However, several very interesting sources acquired shortly after the fire have made it possible to launch the restitution project.

3.1 Architectural survey

They are in particular made of work carried out by Rémi Fromont and Cédric Trentesaux during the professional training of the Centre des Hautes Etudes de Chaillot, France. This work, mentioned in the introduction, had several objectives. On the one hand, to compile the existing documentation on the cathedral's framing, then to make a critical analysis of it. It also aimed to develop and test an efficient survey method, adapted to this type of monumental object: how to survey - in the dark - a 100-meter long, 12-meter span, 10-meter high framing, which is composed of several thousand pieces of wood? The study also sought to understand and describe the medieval framing of the cathedral, and it focused on describing what had never been looked at in detail before: markings, replacements, repairs, reinforcements and lifts. Finally, the last objective of this work was to establish the sanitary assessment of the framing and to identify the pathologies that affect it [7].

This study consists of four general views: a cross-section to locate and identify 26 main frames (Fig. 1) and 98 secondary frames, a longitudinal section towards the south in the axis of the ridge (1:250), a plan of the medieval framing (1:250), a longitudinal section towards the south detailing a part of the choir's bracing (1:100). There are also 26 east-facing elevations describing the 26 main frames, supplemented by some additional views (one CAD, one west-facing elevation, visual findings, typologies and repairs). The eastern end of the frame is specifically documented (in sections and sketches) because of its complexity and historical interest. Two secondary trusses, one for the nave and one for the choir) are represented with a level of detail equal to that of the main trusses. Farm lifting assumptions are also presented in axonometry. Various sketches provide information on the means of lifting and on the metal tie rods. Marks present on the timbers are identified and located in plan view. Specific joints made on the rafters are also documented in plan.

3.2 Photographs

In their study of existing documents on medieval framing, the two architects did not mention the thousands of photographs taken by those who had access to the roofs of the cathedral, notably architects and researchers. A significant fraction of this data was produced by R. Fromont and C. Trentesaux themselves during the above described survey. More than 3500 pictures (1.86 Tb of data) related to the carpentry and roofing have been collected and partly processed for deposit in the Huma-Num Box and ArcheoGrid portal. These treatments concern in particular the indexing of the images based on existing and custom thesauruses. Eighty keywords are used to identify the trusses, the area photographed according to the nomenclature in place on the site, the altitude of the main point and the viewing direction of the camera (principal axis) of the photograph.

A statistical analysis reveals the heterogeneity of the photographic coverage. In fact, the structures at the eastern end were the subject of a very large number of photographs while the medieval spans on either side of the spire are less well documented. The photographs provide crucial information on certain assembly details that were consciously exaggerated in the architectural survey and not very visible in the laser surveys.

3.3 Laserscanning

Cathedrals are complex objects to digitize [15], the framing even more so. Experiments on similar objects have shown significant limitations [16] related in particular to the effects of masks present at the time of acquisition and which limit the interest of a method based solely on this type of data. Even incomplete, they remain a source of information of great importance for geometric properties (Fig. 1). Our approach benefits from the unprecedented contribution of experimental data not used in previous studies [17] of the framing. Thus, no complete survey campaign of the attic space, taking into account the specificities of old frames, has been conducted.

These include 3D laser surveys from Andrew Tallon [18] of Vassar College using the Leica P20 between 2010 and 2012 in PTS format. The data contains about 1 billion 3D points with their enriched intensity and RGB values. The quality of the point clouds makes it the reference for the consolidation of other geometric data. However, it is of limited interest for the study of the frames since only two stations were made in this area: the data acquired by these stations represent less than 4% of the complete cloud. The second point cloud is from the company GEA, together with Life3D company, who have digitized by 3D scanner some parts of the cathedral of NDP for Europe Échafaudage scaffolding company, in order to provide them with plans, elevations, sections, as well as 3D models. In April 2018, it was the transept frame that was modeled with a spatial resolution of 1mm. The cloud of 1.473 Gb points is in PTS format. 95.5% of the data is related to the framing. The last point cloud was produced by the company Art Graphique et Patrimoine in 2014. Unfortunately, we did not have direct access to their point cloud, but to several dozen sections of the data. Of the three surveys, this is the one with the best coverage of the framing. It should also be noted that Rémi Fromont and Cédric Trentesaux recorded more than 25,000 points using a total station during their study of medieval framing.

Following the April 2019 fire, the *Forest* was destroyed and a large amount of rubble was deposited on the ground floor as well as on the extrados of the nave, chancel and transept vaults as a result of the collapse of the building's frame and roof during the fire. The magnitude of this event has considerably degraded not only the physical integrity of the cathedral but also the accessibility to its various parts. As a matter of fact, it has also endangered the physical safety of the operators brought to work on the site since then.

Obviously, the nature of the actions carried out on the spot has been strongly questioned insofar as we went from a restoration site to an emergency situation requiring immediate actions to secure the building itself but more specifically all the endangered elements threatening to collapse in the very short term.

Henceforth, the destination of most of the surveys carried out concerned a set of actions dedicated from now on to the thorough understanding of the event and to the choice of the strategies to be adopted in order to provide as soon as possible the safety of the cathedral but also of the workers involved in the rescue process. In particular, the extrados of the vaults arouses the interest of the project management - whose actions have been strongly reoriented - insofar as they collect the charred remains of the collapsed framing which will be a precious source of data allowing the study and the understanding - as stated above - of the technical context accompanying their construction as well as for the reconstitution of the fire's dynamics. A detailed diachronic restitution of the geometry of the vaults and the debris was essential in order to document by stratigraphy the relative and absolute location of the remains of the framing but also to highlight possible deformations of the vault before and after the fire as well as in the course of clearing.

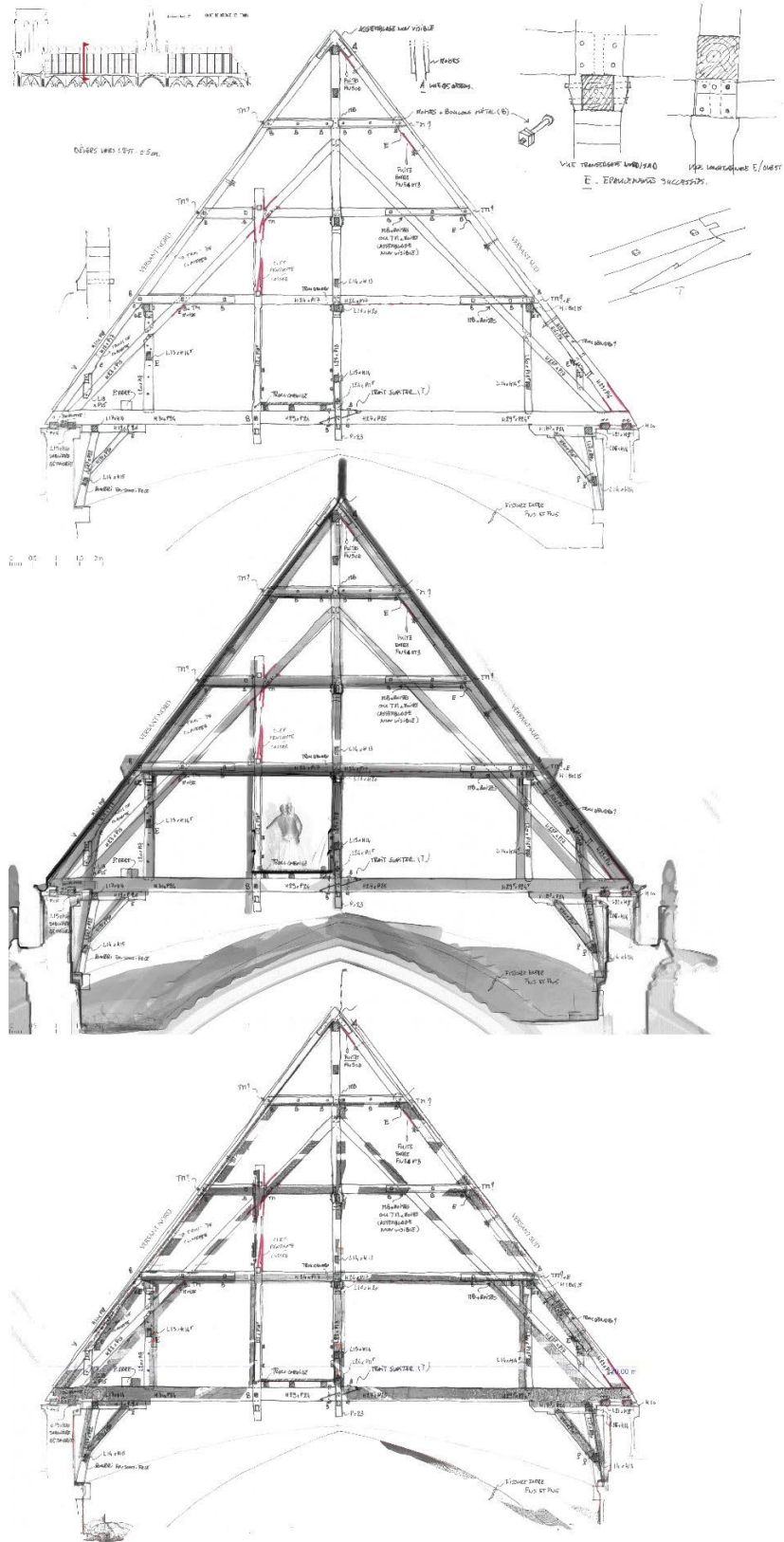


Fig. 1. The N06 frame seen towards the East from the Rémi Fromont and Cédric Trentesau survey (top image), and two photomontages superimposing this survey on point clouds on two sections extracted from the AGP (middle view) and GEA (bottom view). © K. JACQUOT/MAP/Vassar College/AGP/GEA/Chantier Scientifique Notre-Dame de Paris/Ministère de la culture/CNRS

A laser scanner survey was performed in the aftermath, shortly after, the fire by Loïc Espinasse from Archeovision lab [19]. Part of the extrados covering the choir of the cathedral was digitized using a Leica BLK360 laser scanner (Fig. 2). This tool has the advantage of being compact, light, and relatively accurate with respect to the expectations and characteristics of the objects to be surveyed. It has also the possibility of being controlled remotely and of being able to visualize in real time the assembly of the various stations and thus to supplement if need be the surveys on site with complementary stations justifying the use of this apparatus. The preliminary study of the site allowed us to estimate the number of stations to be realized at 36 (three stations for each of the twelve bays to be documented). In the end, 300M points were acquired in two half days with an average ground sample distance of 2 cm.

In addition, 61 pieces of wood found on the floor of the nave, near the transept crossing under the hole in the vault caused by the fall of the spire, or brought down from the extrados of the vaults to free up the eaves walls, were photogrammetrically processed by Olivier Girardclos and Frédéric Epaud of the Wood and framing Working Group as part of a specific detailed study that allowed some timbers to be relocated in their original position. Each of the faces of these timbers is thus completed with an orthophotography carried out according to a protocol that does not allow the generation of a three-dimensional model.



Fig. 2: Rope access technicians moving away from the scanner positioned on one of the rails mounted for the occasion under the technical floor covering the extrados of the vaults of Notre-Dame de Paris. (c) Notre-Dame: building a digital monument, 2020. <https://images.cnrs.fr/video/6934>.

3.4 Photogrammetry by cable cam

The meticulous observation of the deposited rubble, of whatever nature, constitutes a precious source of scientific information that can allow a better knowledge on the constructive and methodological techniques employed during the construction of the cathedral. As Véronique Vergès-Belmin of the LRMH points out, the extraction and in-depth knowledge of the samples taken from the roof should not only make it possible to recover the necessary parts that can be reused or to make copies that conform to the original, but also to advance knowledge: where do the materials come from, from when do they date, so that each element can serve as a model in the hypothesis of a validated identical reconstruction [20]. The work of removing and analyzing the rubble is therefore programmed in sequence with the

restoration and consolidation operations, which must not be disturbed by the technical operations, which are often large-scale and require a temporary halt to the work. The archaeological task thus defined needs to be documented in a precise, chronological and detailed way. It must give a step-by-step account of the volume, nature and precise location of the objects extracted in order to ensure optimal traceability so that they can be interpreted and analyzed in their precise context.

Besides, the congested extension of the site (technical floor covering the top of the structure at a short distance from the subject to be surveyed), the presence of permanent and temporary obstacles (debris and technical equipment used for clearing operations, etc.), the masking of GPS constellations, the low ambient light and the aerological conditions (swirling winds, etc.) make the use of aerial vectors like drones very delicate if not impossible. Operational constraints of certain sites have sometimes required the development of specific devices without which the planned photo campaigns would have been impossible. This is the case, for example, for the survey of Keith Haring's vertical fresco at the Necker Hospital in Paris, for which a carbon crane, designed and built within the UMR-MAP and operated from the roof of the building, allowed the systematic survey of the painted façades [21].

In the case of Notre Dame and in order to deploy a periodic photogrammetric recording, a specific system was developed to meet the challenges of availability, adaptability and reliability: in this respect, we had the idea of a cable cam that would fulfill the expectations listed above, with the advantages of being an existing, mature and immediately available technology. A cable cam is able to move along easily positionable wires which materialize repeatable trajectories on demand, it has a minimal footprint and can be operated remotely even out of a direct line of sight. Finally, it offers the possibility to pilot or program specific movements in advance (translations and stops on predefined distances, continuous round trips, change the camera orientation etc.) and to repeat them again and again if needed. However it should allow an easy deployment even for non-expert and/or untrained users, an increased adaptability to the physical context of the site and sufficient reliability with a maximum operational safety level. The initially chosen configuration - a NOXON compact robotic nacelle with a stabilized RONIN gimbal - only partially met the stated specifications: the preliminary digital geometrical simulations pointed out the fact that - if the cables were located just below the wooden beams placed on top of the upper walls - the suspended camera would occasionally come up against voluminous debris or even the top of the vaults of the choir and the nave. Its relative complexity of use would require the joint intervention of several operators. Because of its dimensions, the device could interfere with the clearing operations in progress. Furthermore many round trips would be necessary to obtain the number of photos necessary for a global photographic coverage of the area and, despite the remote control and video feedback, it would be extremely difficult to assess in-situ the optimal positioning of the cameras with regard to the technical requirements necessary to obtain a sufficient coverage ratio for the photogrammetric process. Finally, it must be said that only specially trained operators have access to the cables previously installed above the void in order to set up the nacelle and to operate the unit by means of buttons and sliders that are difficult to reach with the mandatory safety equipment (gloves, filtering masks, dry suits, etc.).

It was therefore essential to make a number of functional adjustments to this out-of-the-box solution in order to overcome disadvantages that could occur on site. These adjustments mainly concerned a major reconfiguration of the payload package in order to meet expected needs: the ease of use and a single operator control: so, the whole payload support has been redesigned to optimize the compactness and the distribution of the suspended weights; an effort has also been made to improve the readability of the available controls and the ease of triggering the related mechanical actions. The system was finally designed to be easily transportable in the most compact way possible in order to facilitate the mandatory lead decontamination operations when entering or leaving the site. We had also to reconsider the suspended camera positioning for the reasons stated above: a single camera would need a lot of time to perform an efficient coverage of the vaults that might also overcome the battery lifetime of the cablecam system itself. We had the idea to use two SONY RX0 Mk2 compact cameras, placed back-to-back onboard, looking downward with a 45° angle and placed with a 45° orientation to the linear trajectory

of the system. A protruding carbon rod attached to the pivoting head mechanically triggers the built-in gravity driven mechanism by 90° when it encounters a stop device, a hanging rope or a knocker on its route.

This said, we needed a simulator that would allow us to anticipate the best possible placement and orientation of the cameras so as not to lose time once on site. The idea consists to create a digital replica of the cameras that will be used during the survey and that allows to virtually appreciate the effect produced by their placement and their juxtaposition « in real life ». We then imagined to use a pyramid of emitted light whose beam is superimposed exactly on the frustum of any camera whose optical characteristics are known.

For this purpose, we gathered the optic characteristics of the SONY RX0 Mk2 cameras placed onboard the cablecam during the surveying campaigns (Fig. 3): the following figure summarizes all the factors involved in building the camera simulator:

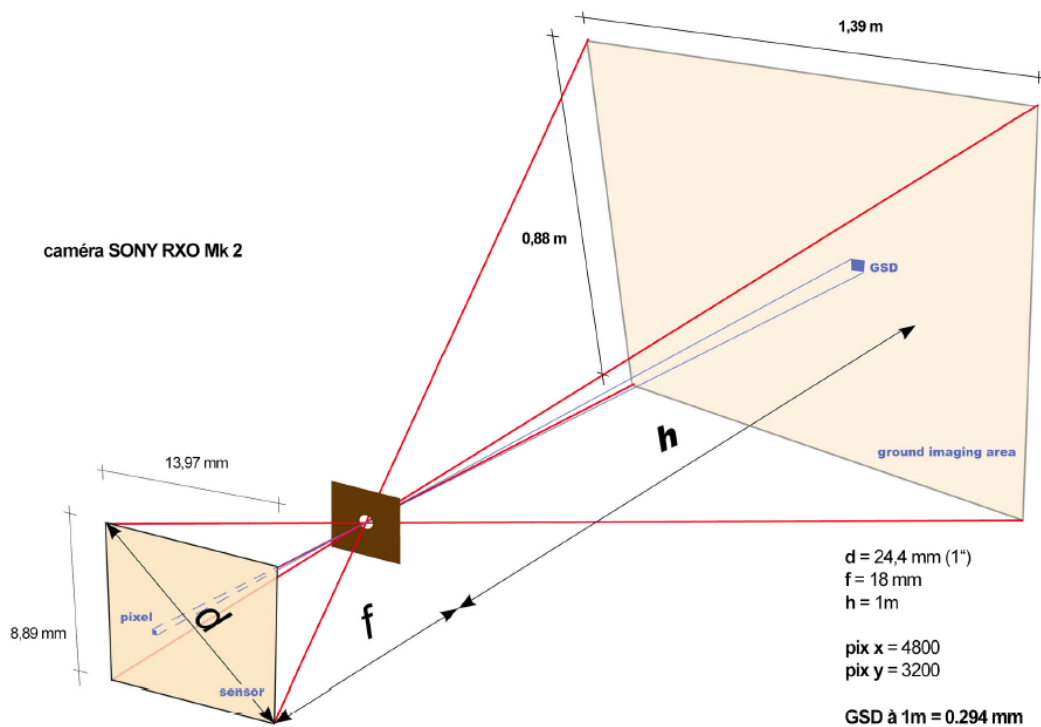


Fig. 3: Schematic view of Notre Dame's camera frustum, main parameters and expected performance in terms of resolution (GSD) and ground imaging area.

First, we put to test these constructor's specifications by doing some manual measurements, placing the camera 1 meter away in front of a white wall and drawing with a black marker the extreme visible portion of the digital image, visible on the built-in LCD screen.

Yet, we noticed a slight difference between the calculated parameters and the measured marks on the wall but we finally considered the most unfavorable conditions for the upcoming experiment, resulting e.g. in a smaller ground imaging area.

This so-called "inverse virtual camera" uses a spot source created with the "spot light" attribute in an Autodesk Maya© scene. There are some specific modifiers including the GOBO function which makes it possible to model the luminous frustum using a specific texture mask (Fig. 4). We will also use the linear light attenuation attribute to approach the effect produced by the camera distance to the subject so as when putting the model to test, a better amount of measurable light on the final rendered surface will globally predict either a better coverage or a shorter distance from the camera to the subject.

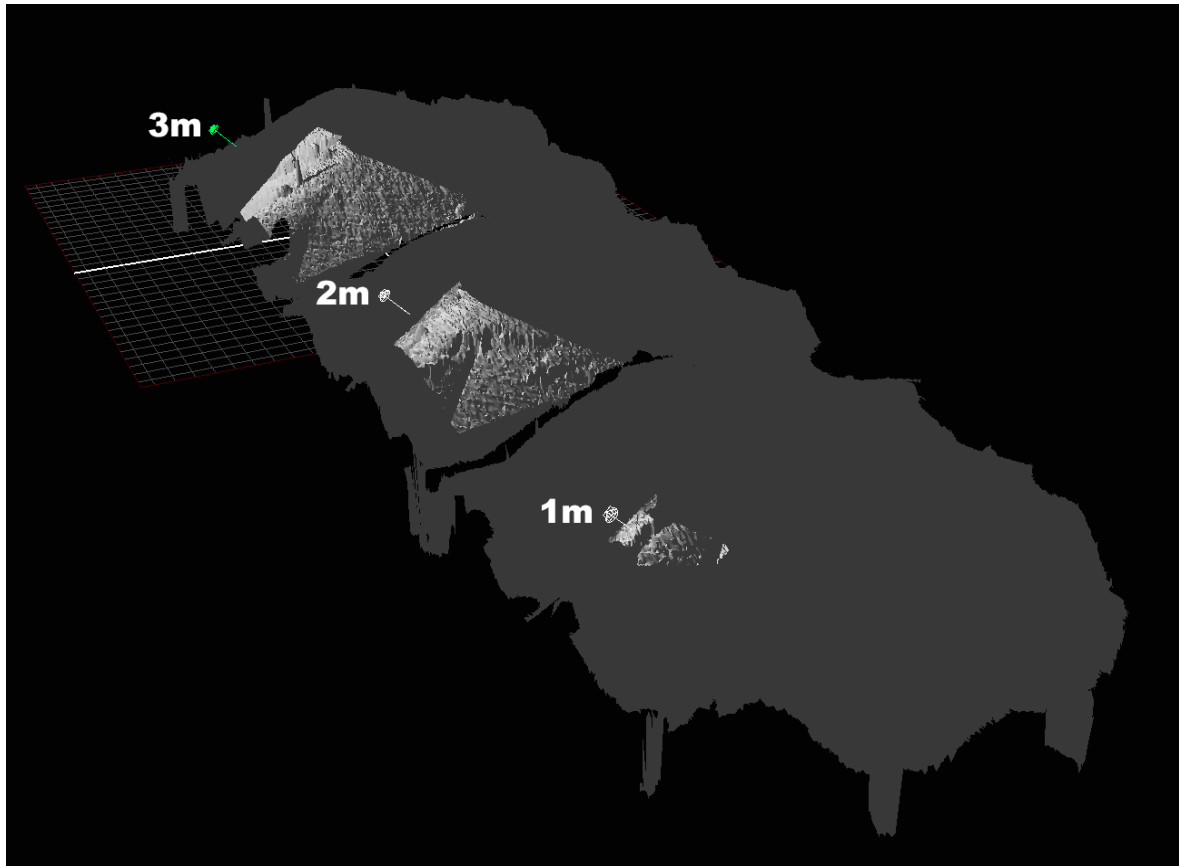


Fig. 4: The «inverse virtual camera » put to test above Notre Dame's vaults with the visible ground imaging area at 1, 2 and 3 meters distance.

Preliminary simulations stated that the 2 cameras configuration wouldn't suffice to produce a good subject reconstruction, showing a poor covering ratio especially in the central area just below the cablecam trajectory. We then placed a third camera onboard in a « Y » configuration (besides, the 45° downward orientation showed the best simulated results) and we modified the bespoke gravity-driven mechanism now able to perform a 180° turn when reaching the end of the path (Fig. 5). It must be said that the developments related to this subject result from a set of works carried out through scientific partnerships for many years [22,23].

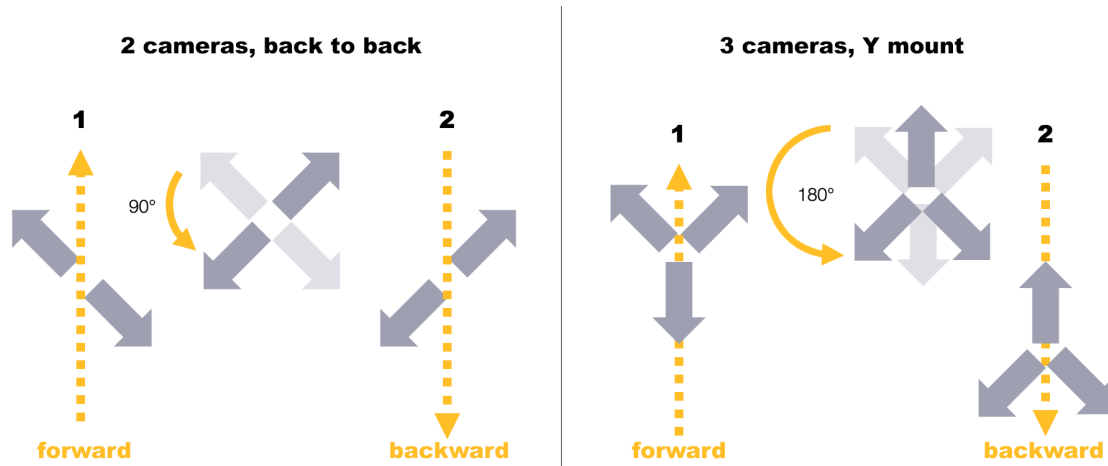


Fig. 5: 2 cameras VS 3 cameras configuration.

If we compare the result of the preliminary simulation calculated using the configuration with three cameras whose orientation in plan and elevation has been virtually simulated together with the timelapse frequency, we notice a strong similarity with the report after correlation provided by the software used (Metshape PRO) which shows - just like in the simulation - a strong redundancy of superposition (Fig. 6), having finally allowed to obtain the best coverage of the site with the result of a strong resolution (1,21 mm/pix) and optimal coverage.

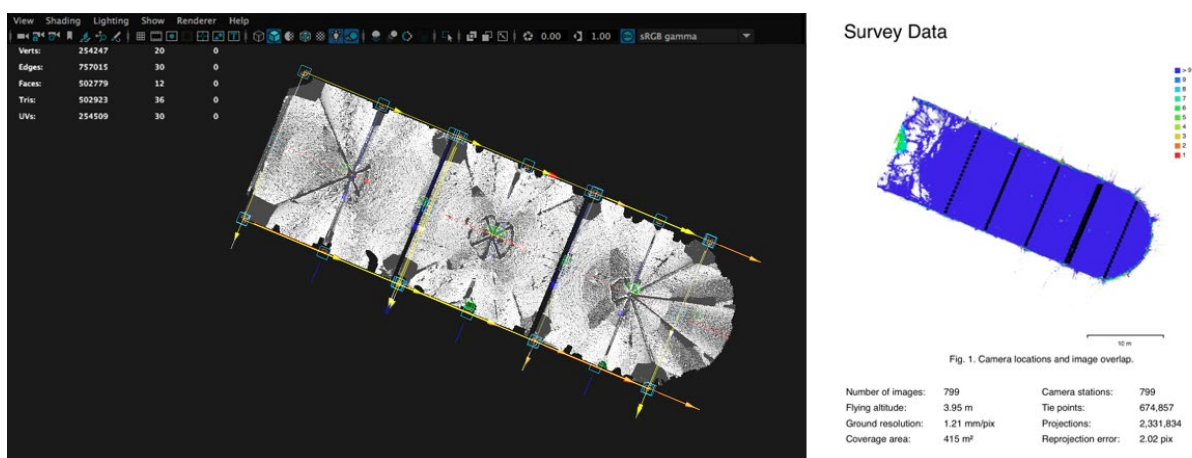


Fig. 6: The preliminary simulation of the cameras coverage and, right, the coverage redundancy of the cameras after the 3D reconstruction process.

Thus, seven different campaigns were carried out, most of them under the supervision of Alexis Komenda, a C2RMF photographer who took charge of the operations based on the operational recommendations previously provided by the UMR-MAP researchers. While the first two campaigns mobilized five operators, which allowed them to finely arbitrate the most appropriate technical options for an implementation "in autonomy", the subsequent campaigns mobilized on site only the presence of a photographer and two rope access technicians ensuring the safety of the operations and the installation of the device on the cables.

4. Results and discussion

The *Forest* had not been methodically and systematically surveyed, which would have resulted in relevant documentation in the sense given by ICOMOS [6], including characteristic samples of redundant materials or elements removed from the structure, and information on relevant traditional skills and technologies. All this data must be collected, cataloged, securely stored, and made accessible as needed. While new surveys were undertaken after the fire to record what remained of the structures using a wide range of tools, it was also necessary to develop customized devices to both operate within the hyper-constrained context of the site and to document the remains of the framing, the last trace of the NDP structure. It is in this context that the concept of cable cam photogrammetry was developed.

4.1 Restitution #1

All the data thus collected were mobilized to produce object-oriented 3D models, discrete representations of the framing that inventory nearly 6000 components through time and space. The processing pipeline is based on the consolidation and spatialization of plans, sections, elevations and 3D models within the virtual environment of 3D computer graphics software. A first stage involved the spatialization of data from the laserscanner campaigns. In particular, this involved the AGP sections (top plate and roof plans, two longitudinal and two transverse sections). This set of documents constitutes the modeling reference frame. This was followed by an initial modeling phase aimed at calibrating the main volumes, in particular the attic space. The main trusses were modeled - for geometry - on the basis of AGP data, or GEA in the absence of a cross-section provided by the former. Sections were produced from the GEA point cloud at farm level where appropriate. Fromont surveys and photographs were used to detail the trusses, in particular the joints. For the arrow, planes were extracted from the GEA point cloud at a frequency of every 40 cm and positioned on the reference sections. Each element is identified and can be classified according to its structural function, dating hypotheses, pathologies, markings, dendrochronological samples, etc.

Experiments have shown that it was possible to model NDP [24,25] or ancient framed structures in so-called BIM environments [26]. These technical choices of reverse engineering are above all demonstrations aiming to show, not without difficulty, the possibility offered by certain AEC software, to manipulate objects for which they were not initially thought. Qualified as HBIM, they do not however detail what is the main interest of BIM, i.e., the "use of a shared digital representation of a built asset [...] to facilitate design, construction and operation processes to form a reliable basis for decisions" [27]. However, the NDP project is above all a documentation and heritage conservation project which, in the short term, will help with restoration work. It federates actors of the sciences of the heritage with knowledge and know-how of a very great diversity for which the BIM alone is not an adapted answer.

However, the collaboration around the data produced on the framing presents a specific issue with regard to the data on the parts still existing. The efforts of the Digital Data WG are turned today essentially on the visualization and collaboration based on point clouds representation. While the data relative to the remains of the framing obtained by cable cam for the extrados were naturally integrated into the NDPV prototype, experiments are underway for the mesh model of restitution. Tests were conducted with the Visual Computing Lab (ISTI - CNR) to evaluate the relevance of the Visual Media Service [28] for web access to the restitution. Other possibilities based on JavaScript libraries, like IFC.JS, are also being studied.

4.2 First applications

Evaluating the geometric accuracy of the rendering is a challenge, given the synchronicity in the progress of the various involved parties' respective projects. The virtual restitution of the framing was thus made available to the project management in September 2020, as one of the basis for an actual reconstruction [29,30]. However, due to the tight schedule, no feedback has yet been received from them,

even though the knowledge acquired during the project would certainly lead to corrections to the model. The model has been widely shared outside the scientific area, notably in favor of television media, or in the video game and film industry in order to address the problem of ahistorical CGI [8].

The model is available to the scientific community of the scientific site, in particular the Wood and Carpentry WG, but also the Structural WG for fire simulations. Due to a delay in the Wood and Carpentry WG project, it is only now a partner able to provide input on the geometric accuracy of the model. It has also been integrated into *nd-viewer3D*, with the other data: a 3D data visualization environment for NDP in which the Tallon survey was established as a reference (Fig. 7). The geometric restitution and its attribute data constitute a reliable support to carry out experiments and analyses aiming to improve the state of knowledge on this space and to generate by iteration new and more accurate versions. It is also a tool that aggregates new data, which facilitates their exploitation through this common digital environment. For example, 61 dendrochronology samples were collected from 1991 to 1996 during four successive campaigns (two in 1991, one in 1994 and one in 1996). Their location remains ambiguous, in part due to numerous errors in sample naming and the limitations of orthographic representations for locating samples in the extremely dense space of the *Forest* [31]. With the help of photographs, the restitution makes it easier to relocate, manage and analyze these sets of information.

Another example is the amount of wood in the frames. Unlike methods based on typological models [17], the restitution makes it possible to take into account the dimensional specificities of each of the trusses, as well as the whole frame, in order to produce more accurate estimates, particularly with regard to the volume and therefore the mass of wood used for the construction of the framing.

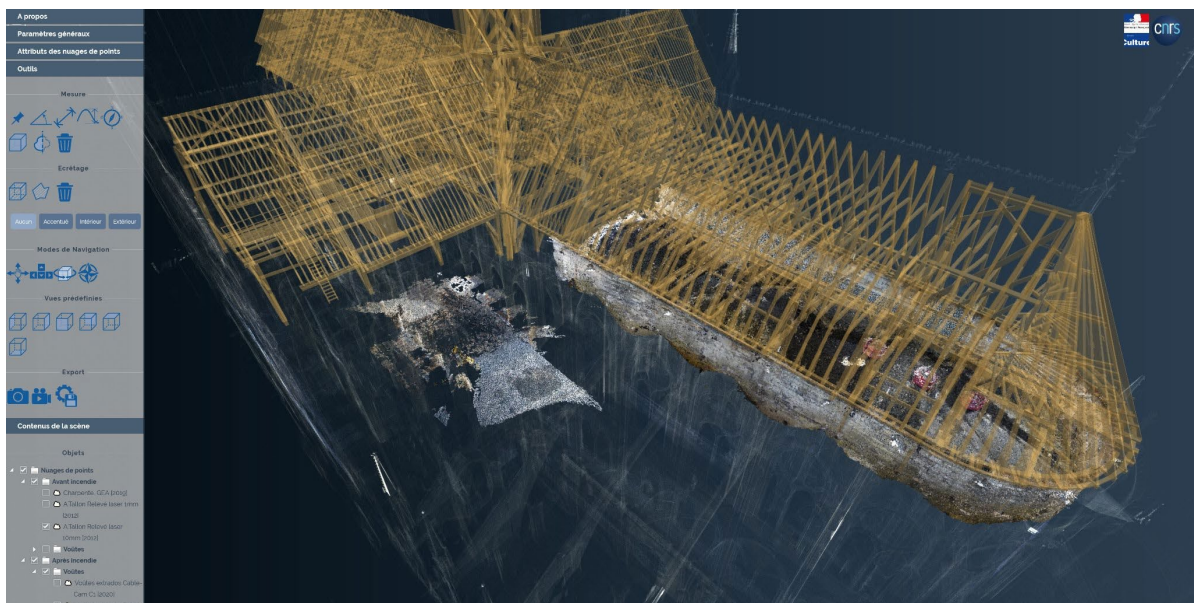


Fig. 7: 3D rendering of the frames superimposed on three different point clouds: the 2010 survey by Andrew Tallon, a cable cam survey (06/2020) and a (07/2019) survey, in the online viewer NDPV. © V. ABERGEL/K. JACQUOT/R. SALERI/MAP/Vassar College/AGP/GEA/Chantier Scientifique NDP/Ministère de la culture/CNRS

On the other hand, this work site represented an unexpected and extremely valuable platform for experimentation, allowing the testing of acquisition protocols already practiced in our laboratory for many years. The example of the cable cam, evolving in an extremely degraded context, forced us to reconsider what we took for granted in terms of sensors and vectors. Moreover, the prohibitive conditions of access to the site have motivated the need to prepare with much more precision the actions planned with custom tools able to simulate the effectiveness of the planned camera placements and to potentially pinpoint the areas likely to cause problems. Of course, it is rare to find so many constraints gathered in a single survey campaign; however, the cable cam used at NDP has shown many advantages

that will be interesting to exploit in the future, especially indoors, where working conditions (poor lighting, masking of satellite constellations, etc.) do not allow for the use of positioning aids that are easy to use with outdoors operations (artificial vision, GPS, etc.). It could also operate on vertical structures (interior facades, load-bearing elements, etc. for which it will be necessary to perform autonomous periodic surveys, remotely programmed or triggered on demand. Finally, it would be compatible with highly constrained environments (underground, caves, polluted environments, etc.) in the total absence of external references and with great spatial stability (recalling the simplicity of the self-positioning action which is permanently measured along a cable with the revolutions count and the speed of rotation of the driving roller), mandatory in the field of multi-spectral campaigns that will be shortly experimented by the UMR MAP (pulsed laser, raman libs spectrometry, etc.).

5. Conclusion

The restitution is not an achievement but a full-fledged tool of the research process that allows collaboration, like a digital model, to test certain hypotheses, but it is also an environment capable of evolving as knowledge about the modeled object changes. Beyond the actions carried out by the Digital data WG, the contributions of the various working groups have made it possible to bring together the expertise of the actors involved through an absolutely unprecedented scientific and operational intersection. It has not only allowed for the development or optimization of professional skills already consolidated by every single group, but has also made everyone aware of the need to make various approaches interoperable, each with its own set of tools, methodologies, points of view and datasets. The parallel development of software that not only brings to the front available knowledge, but also allows for its cross-fertilization, leading to a decompartmentalization of competencies and a transversal and constructive reading of the possible issues. Without this openness, the development of increasingly sophisticated technologies would turn any large-scale heritage project into a new Tower of Babel.

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