3D SOLID REPRESENTATION AND VISUALIZATION FOR LARGE HETEROGENEOUS SITES WITH URBAN AND RURAL HERITAGE - A CASE STUDY

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ABSTRACT:

This article introduces usage of 3D solid modeling methods in order to represent and visualize highly complex environments such as large heterogeneous sites integrating urban and rural heritage content. The theoretical bases of a new simulation system implementing this approach will then be detailed. The article will present a case study concerning urban and rural sites 3D solid modeling for the state of Vermont. Finally, it will discuss the various challenges to face in order to extend this use case to other states. This approach virtually enables interoperability between the various sources of legacy data, federating them in a 3D Solid dataset representation, designed for large heterogeneous sites.
The first part of the article focuses on theoretical problems: multi-model architecture problems, legacy digital representation and mathematical surface models applied to architecture. It then introduces the proposed approach in terms of geometric description and graphical rendering principles. Such theoretical bases allow defining new generation paradigms for the creation, management and deployment of large 3D Solid Datasets.
The second part of the article presents the Virtual Vermont project, which implements the proposed approach, integrating within the same simulation environment various data sources, including heritage, GIS, infrastructure and enables a wide number of applications.

1. INTRODUCTION

Level Of Detail (LOD) is the main measure of complexity for tridimensional scenes, especially for city, building and terrain digital models.
Introducing such a hierarchisation for spatial information has become necessary, given the growing memory footprint required to store all the geometric information, then for graphical rendering during visual simulation.
For a number of theoretical reasons, and also because of certain legacy practices which are yet to be reassessed, polygons and especially triangles have become the normative graphical and geometrical units for 3D virtual worlds.
Their proliferation, out of any geometric control, can only be constrained through minimizing the target precision of objects, with drastic reduction of polygonal resolution (ex: decimation), or through suppressing level of details for certain application contexts (ex: distance).
Such a worst common denominator approach between models polygonized geometry and polygonal graphical rendering is initially of a theoretical nature: the algebraic and algorithmic nature of triangle-related problems, favours extremely simple implementation, both at the hardware and software levels.
In such an environment, computing coordinates for a point being part of a line and a triangle is a first degree algebraic problem, and its maximal simplicity ensures real time repetitive computation for z-buffer type graphical rendering (graphic cards) or raytracing (parallel computing). This simplified approach of mathematics constitutes the main reason of polygonal simulation systems' success, intensive use of triangles, and, paradoxically, of major problems originating from it.
This article introduces the antithesis of conventional polygonal practices, since it describes, through a case study, a volumic simulation system's architecture, storing tridimensional information from variable degrees of polynomial representations.
This approach also enables unification, compatibility and interoperability for geometrical, physical and graphical computation.
Polygonal representation is then either discarded, or processed as a particular case, where triangles are represented from second degree algebraic inequation systems. On another note, in the proposed system, the degree choice for volumic forms will follow variable levels of geometric semantics for the modeled objects.
Finally, the LOD notion, initially depending from polygonal representations, will thus evolve, integrating the notion of algebraic complexity, defined from minimum and maximum levels of the geometrical forms met during simulation scenes modeling.

2. VOLUMIC SIMULATION SYSTEM THEORETICAL PRINCIPLES.

2.1 A Multi-Model Architecture

Hyperlarge, hypercomplex tridimensional scenes simulation actually depends on digital models, generated from virtual geometrical forms synthesis, either as designed or as built, and

spatial data analysis produced models, through measures and scans performed on existing, real physical objects.
The two approaches, synthetic and analytical, can complement each other, as long as a perfect interoperability is ensured between resulting digital models, which can be done, on one hand, from assessing a full mathematical compatibility, on the other hand, from specializing computational processing to adequate models.
Choosing multi-model simulation architectures is especially required for scientific simulation applications, for which interrelations between geometry, graphics and physics (Visual Simulation or VizSim) are omnipresent.
Finally, on top of Level of Detail (LOD) and geometry algebraic complexity, the level of domain specific expertise embedded in a model, as well as the surfacic (hollow forms) or volumic (solid forms) representation type for tridimensional objects are essential evaluation and hierarchical classification criterions for simulation oriented digital models.

2.2 Various Digital Representations for Buildings and Cities

Representing in a digital form an architectural building is a complex problem, which can be approached from three different angles, depending if one focuses on design process, formalizing rules and logics underlying relations between forms and geometric spaces, or focuses on construction process, formalizing physical relationships between elements and materials, respecting the designer's geometrical directives, or finally the restitution process, formalizing the existing geometrical and physical state of all or part of the building at a given date.
The three possible digital models generated from these three distinct approaches rely on extremely different theoretical mathematical bases.
The highest geometry semantic level (Surface equations, topological relationships), as well as architectural semantics (Styles, construction rules), is naturally present in the design model, which, ideally, focuses on storing the building intelligence, based on high level programming languages (ex: SGDL) (Rotgé J.-F., 1996) (Rotgé J.-F., 2000) or based on forms or style based grammatical systems (Stiny, 1980).
The construction model must be structured as a constraint based graph, and must describe constitutive physical elements. This geometry must allow discretization, relying for instance on meshing techniques to enable acoustic, thermal and structural integrity simulation computing.
When considering scientific simulation, the two first models are thus mandatory in projects preliminary and initialization phases, and must tightly interact, the mathematician and computing theorician assuming the responsibility on the architect's design models, the physician and digital computing specialist managing the construction model.
The restitution model produced from spatial information acquisitions or scans (Photogrammetry, LIDAR, …) do not embed any explicit intelligent information. Data can be processed and segmented in order to allow further geometric retroanalysis, through shape recognition techniques.
Finally, for real time simulation application, whether visual or integrating intervisibility or collision between objects, a fourth type of model must be generated and updated from the information extracted from previous models. This fourth model has to be optimized for purely geometric or graphics intensive computation.

2.3 A short survey of Mathematical Surface Models for Architecture

If Platonic and Archimedean polyhedrons, pyramids, prisms, the sphere, the cylinder, the cone are used since antiquity as base architectural components, a real theoretical study on their subject only starts at the beginning of the XVIIIth century, with Frézier's treaty on stone cutting, which constitutes the first work dealing with spatial geometry. Intersections, truncations and combinations of such elementary forms allow building more and more complex geometric sets.
In spite of Claude Parent's discovery in 1700 of the sphere's Cartesian equation, recurring to algebraic equations for analytical formulation of spatial problems will only develop from Mézière Engineering School around 1760. With the increasing mastery upon algebraic tools, the idea of classifying geometric forms appears quickly, beginning with bi-dimensional space forms.
This is why, since Descartes' works, mathematical description of curves and surfaces has followed an enumerative approach, aiming to classify mathematical forms from their algebraic equation and properties. This school has further been developed by Newton, Stirling, De Gua de Malves, and Euler results in a combinatory dead end, due to the expansion of families number and particular cases, even if only considering low degree curves study, of the 2nd, 3rd and 4th degree.
Gaspard Monge, in 1770, replaced the former, enumerative method with the generative method, grouping surfaces from their generation mode. He studied the proprieties of all orders of cylindrical surfaces, then conic and revolution surfaces, and so on, regardless of any algebraic hierarchy.
According to Arago, Monge judged that when faced with a choice of surfaces for a given objective, designers do not consider equations degree but hesitate between surfaces submitted to a same generation mode, whether they are of the second or thousandth degree. With the international impact of descriptive geometry from the beginning of the XIXth century, shortly followed by drafting techniques, architecture essentially becomes a constructive method aiming to assemble elementary surfaces or parts of them, regardless of their algebraic degree.
Nevertheless, other properties, such as surface curvatures, will become mandatory to enable proper surface choices and complex structure elaboration, especially the ones made of concrete (Gheorghiu A., Dragomir V., 1968).
Recently, certain types of surfaces defined as parametric (Nurbs, Bézier, …) have begun to appear through their usage by architects and software systems, initially dedicated to automotive and aeronautics design.

2.4 Various Digital Representations for Complex Objects

The objectives are two-fold and illustrated on above diagram (Fig 1) by the two discs schematizing unification and interoperability processes. The unification objective consists in developping a unified mathematical environment for numerical representation and processing relative to geometric, graphic and physics problems. The interoperability objective aims to design and deploy adaptative computing architectures able to second and, in the medium term, replace existing complex processing architectures in all simulation applications.
Digital datasets, resulting from the different kinds of software allowing 3D models creation, must necessarily coexist in a mathematical way, in order to enable integrated simulation applications.

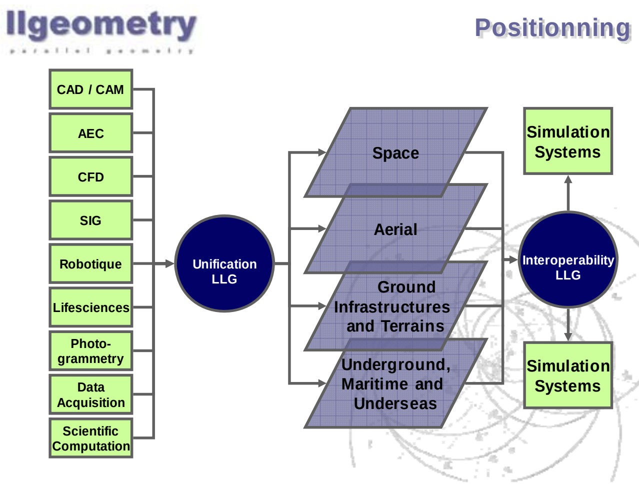

Fig 1 – Objectives Positioning

In existing simulation applications, in spite of its numerous shortcomings, the triangle is the only mathematical common denominator enabling an interoperable and integrated approach of all different simulators components, geometric, graphic, physics.
The first objective is to eliminate the triangle as the only description and memorisation unit for 3-dimensional geometric information. The fundamental problem is thus to focus on triangle generation and its underlying technical and theoretical rationale.
The second objective is to eliminate the triangle, this time as the only graphical rendering unit for visual simulation applications. The fundamental problem, in this instance, is to develop new generation graphic pipelines, directly displaying complex surfaces on screen, without any elementary triangle discretization (Tesselation step).
The general aim is to provide a real simulation system, operating on a multi-layered environment, inter-related and inter-dependant : space, aerial, ground infrastructures and terrains, underground and maritime, underwater spaces.

2.4.1 Simulation of complex volumic objects

To enable taking in account geometry and physics interrelations, it is essential that 3D models are volumic, i.e. allow operations on matter such as sections. Two different theoretical approaches (Kolbe T. H., Plümer L., 2004) are generally used to provide a volumic description for 3-dimensional objects.
The first approach is essentially constructive, the different steps of matter operations being implemented in the form of arborescent representations, from implicit surfaces. Typically, these surfaces, called elementary primitives, are combined to constitute complex objects. Such combinations enable for instance sectioning, or merging matter through successive steps which are described in an arborescent form called volumic tree. This approach is applicable to polyhedral forms (Planar faces objects) and the basis of the modeling system known as CSG (Constructive Solid Geometry).
The CSG approach offers excellent object description compactness, but suffers from severe theoretical problems: geometric and topological bugs, extremely difficult to solve in a proper and rigorous way for computing implementations.
On the other hand, the legacy rendering methods for CSG objects face recurrent shortcomings in terms of memory consumption, processing times and sometimes both at the same time.
The second approach typically used to provide volumic description of 3-dimensional objects is of a declarative and enumerative nature, and uses parametric surfaces. Such parametric surfaces are used differently, since complex objects are constituted from jointed surface parts, assembled like patchwork squares, stitched one to the other. The squares can be flattened and represent the faces of a cube or pyramid, but also curvilinear to represent complex forms. In this approach called B-Rep (Boundary Representation), polyhedral forms are considered as amalgamated polygon sets.
The B-Rep approach is mainly used in CAD-CAM systems, which present theoretical characteristics completely incompatible with the simulation of large 3-dimensional scenes. The quasi necessity to discretize geometry for graphical rendering, computed fluid or solids dynamics or rapid prototyping generates astronomical amounts of triangles. And even before such phases, topological information description (stitching) generates considerable and soon prohibitive memory consumption for its data structures. On top of certain mandatory metric information on the object, relationships between vertices, edges, faces and solids must be stored, and their topological consistency maintained through the whole suppression-modification cycle, involved thorough each of the design steps.
Finally, the B-Rep object, based on parametric surfaces, is hollow and usually suffers serious ‘waterproofing’ problems at the joints between surfaces. For visualization or computed fluid dynamics simulation, certain mathematical stitches are not correctly represented and allow penetrating inside the object. The object’s geometry must then be repaired, which requires complex and work intensive interventions.
Contrary to the above methods, the universal 3D solid format proposed in this context, detailed in (Rotgé J.-F., Farret J., 2007), originates from the unification of all geometries comprehended by a complex urban model. The approach hereby detailed is based on a constructive description system for the geometric environment, providing an exact volumic definition of complex urban scenes without making use of classic polygonal description methods.
This constructive system, developed upon Arithmetic of Forms (Rotgé J.-F., 1997) enables controlling classic volumic systems such as CSG, B-Rep and voxels, while optimizing and considerably reducing computing times and memory resources required for highly complex urban simulations.

2.4.2 Graphical rendering

The visual representation of 3-dimensional objects is without any doubts the weakest link of existing simulation systems, especially when managing large scenes or complex structures. Such legacy systems suffer from an extensive memory load (Terrains, infrastructures, urban models).
Existing real-time visualization systems conventionally rely on two distinct approaches, rasterization, and raytracing.
Rasterization, commonly integrated to specialized graphic hardware, is essentially dedicated to large polygonal datasets approximating 3-dimensional objects and scenes. Its principles are simple : colorize in real-time each and every triangle produced from geometric modeling. In this case, objects are surfacic, i.e. hollow from any matter.
CSG rasterization (Stewart N., Leach G., John S., 1998) rather colorizes implicit surfaces, forming matter filled objects. The latest approach is particularly inefficient to medium sized volumic scenes and inapplicable beyond.

Raytracing initially is a software approach, allowing very high quality pictures rendering from triangle sets (Surfacic raytracing) or volumic scenes described from implicit surfaces (CSG Raytracing). Real time is reached for large scenes using software methods based on parallel processing, or using very recent, high end specialized hardware.
In the case of Surfacic Raytracing, the huge amount of triangles generated by surfacic rasterization introduces impairing performance bottlenecks.
In the case of CSG Raytracing, severe performance problems are caused by the extensive intersection computation required between rays and the volumic scene's implicit surfaces.

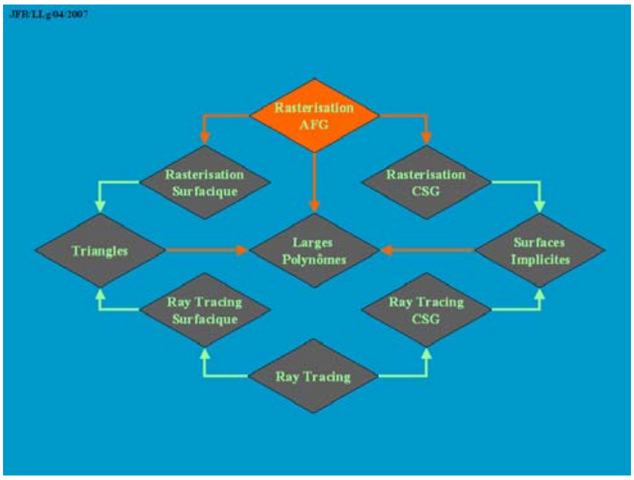

Fig 2 - New Generation Polynomial Rasterization Strategy

In this context, the proposed approach is to develop a new generation polynomial rasterization. As presented in figure (Fig. 3), this rasterization, which consumes volumic scenes based on large polynomials, superset of algebraic and parametric surfaces, is substituted to existing rasterization and raytracing systems.

2.5 Legacy Data Interoperability

Proposed approach is interoperable with legacy data. Data formats range from government standardized GIS formats to normalized GIS datasets. A number of tools and templates, specifically developed for this context, allow rapid development of new conversion pipelines to address the eventuality of specific, non standard formats.
Apart from urban and rural heritage information, typical contents include Site topography, terrain altimetry (topographic sampling, level curves), Cadastral information, Bathymetry, aerial or satellite photographs and data sets, Transportation infrastructure (Roads, rail, maritime and aerial routing, etc…), Public venues / installations (Education, housing, hotels, health, security, …).
Legacy data interoperability is further described in (Rotgé J.-F., Farret J., 2007).

3. A CASE STUDY – VIRTUAL VERMONT

The first phase of the Virtual Vermont project focuses on the development of a reference central database. The nature of provided datasets allowed constituting a hybrid model, integrating and merging conceptual information relative to certain building typologies, especially agricultural, and information produced through photographic acquisition. Given the fact that LIDAR type data were not available, reverse engineering steps have not been included in that phase, leaving aside the adjustment of model parts from information acquired after construction.

3.1 Design Model

Descriptive geometry spanning from stone cutting theory and fortification theory is certainly, before the computer sciences era, the first intelligent graphic language. Combining geometric primitives through intersection or penetration operators enable describing the construction algorithm of a three dimensional object and especially of a building. Associated graphic constructions allow the designer to work without having to consider underlying analytical computations. In such a context, drawing is only involved at the interface level, in order to solve algebraic equations systems out of the reach of users. Translating such complex calculus and such realist 3D visual representation through volumic languages completely frees the design process from any drawing functionalities. Geometric and professional rules as a whole can then be encapsulated in a formal manner, through specialized programming languages.
Such an approach especially allows consigning topological relationships between spaces as well as objects metrics. It thus makes possible to express, in a more general way, all spatial relationships and constraints between the different parts of objects.
Having access to such powerful capabilities, the programmer-designer can then develop an entirely programmable digital model, from applying analysis the building's logical and 3-dimensional proprieties analysis, for any required level of detail.
This approach seems, on one hand, particularly natural and adequate to describe buildings at early stage phases.
But, on the other hand, it possibly requires greater architectural retroanalysis efforts and adequate skills to reconstitute the design logic existing architectural works, which have been sometimes significantly modified.
In the case of wood structure architectures, wood works cutting techniques and static and strength of materials constraints form the theoretical and conceptual basis of the buildings. Thermal and climatic constraints, natural lighting or acoustic control and of course final functional usage of space define and constrain purely aesthetical choices for spatial forms and more generally architectural design.
For certain privileged cases, such as for instance Vermont agricultural heritage modeling, architectural retroanalysis phase is significantly simplified by existing agricultural buildings descriptive geometry works (French T.E., Ives F.W., 1915), (Foster W. A., Carter D.G., 1922), illustrated in figure (Fig 3). \
Volumic programming of standard agricultural buildings then becomes a simple computer oriented translation of set rules for that particular building typology.
Figures (Fig 4 to 6) illustrate, for instance, chronological modeling steps from plans and elevations of a stables prototype to the 3D model.
Once a certain number of architectural libraries have been developed, they can be used to reconstruct existing buildings volumic models.

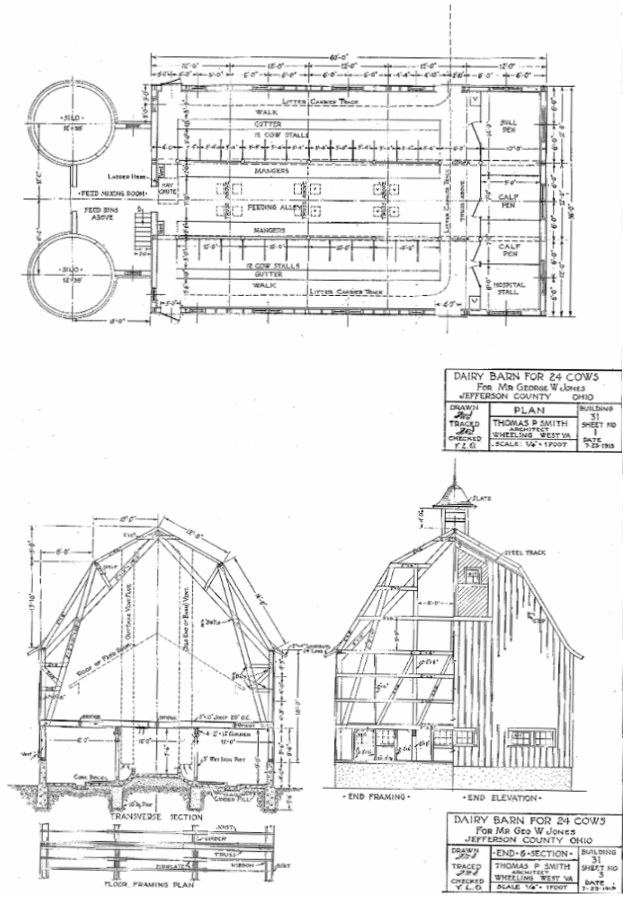

Fig 3 – Dairy Barn for 24 cows - Jefferson Country Ohio

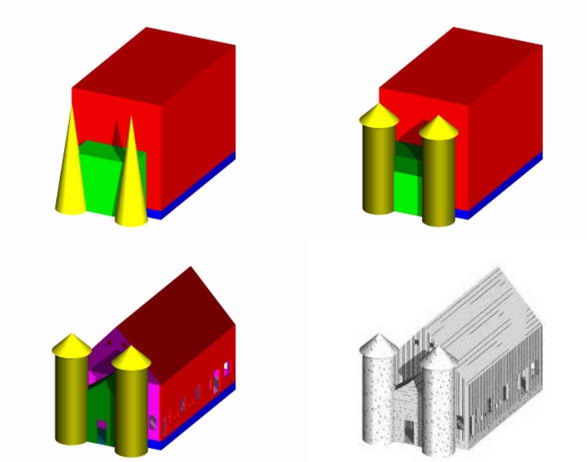

Fig 4 - Dairy Barn modeling steps

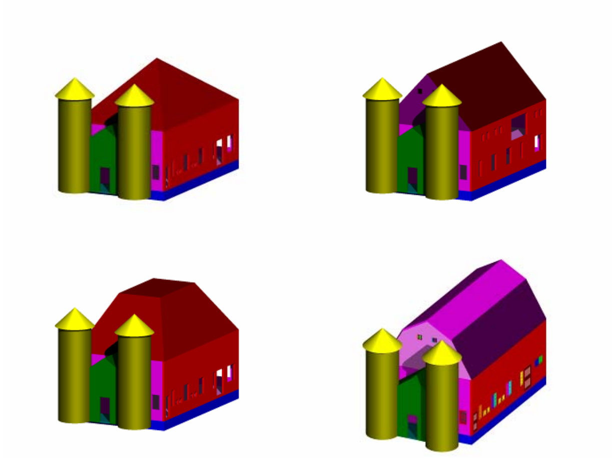

Fig 5 - Dairy Barn various roofing structures

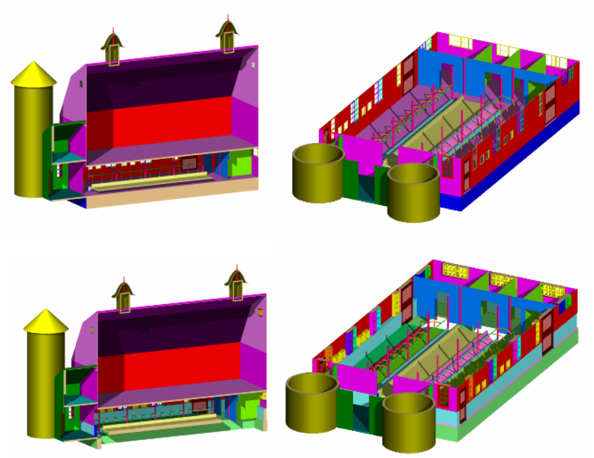

Fig 6 - Dairy Barn inside structures - Two different Levels Of Detail (LOD)

Shelburne Farms haras model (Fig 7) is thus resulting for the application of functions and professional rules, literally organized in an architectural vocabulary (Fig 8).

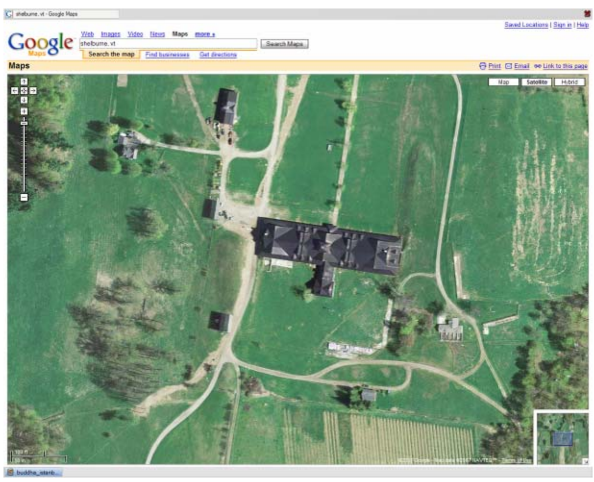

Fig 7 - Google Maps aerial view of one building of Shelburne Farms Rural Heritage Complex

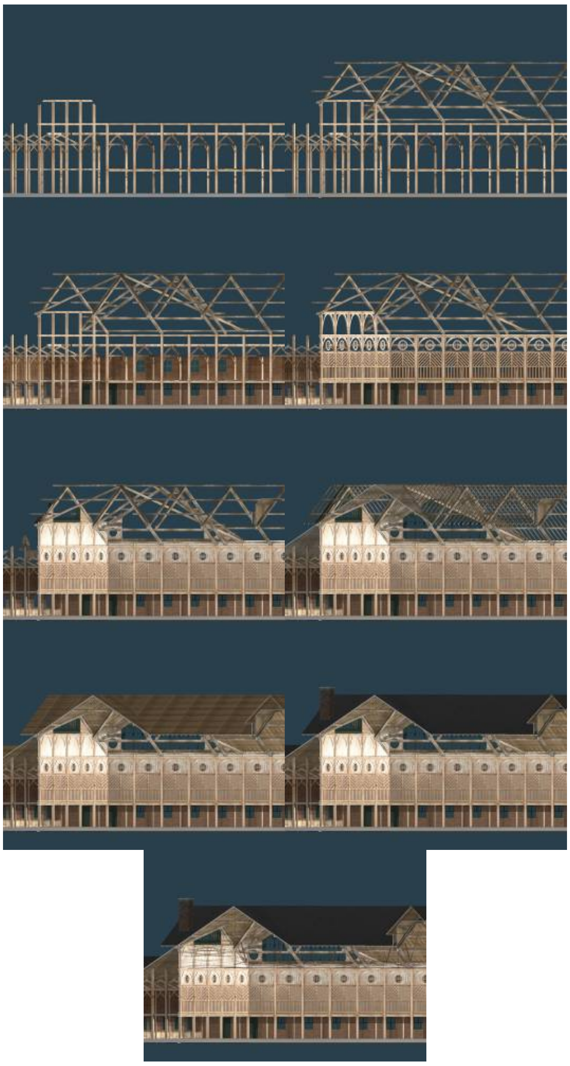

Fig 8 - Shelburne Farms Breeding Barn Construction Phases

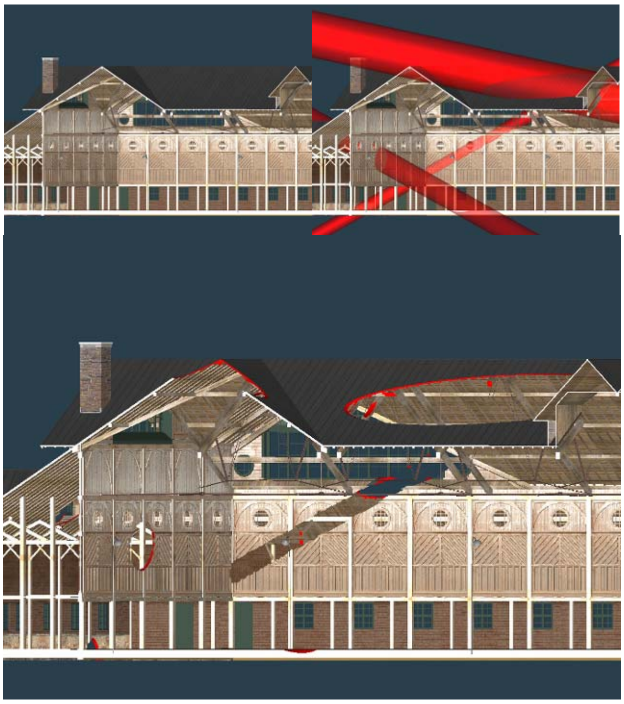

Fig 9 - Volumic cuts in Breeding Barn Structure

Screenshots (Fig 9) illustrate the volumic nature of Shelburne Farms hara (Breeding Barn) model.

3.2 Construction Model

In the context of Virtual Vermont project, two instances of construction models have been generated through retro-analysis : the wind towers site of Searsburg (Fig 10, Fig 11), for which no digital CAD information was available, and the underground storm water draining system of Butler Farms residential area (Fig 12, Fig 13), rebuilt from aerial pictures, and CAD paper information.

Fig 10 - Searsburg Wind Towers Retroanalyzed Structure

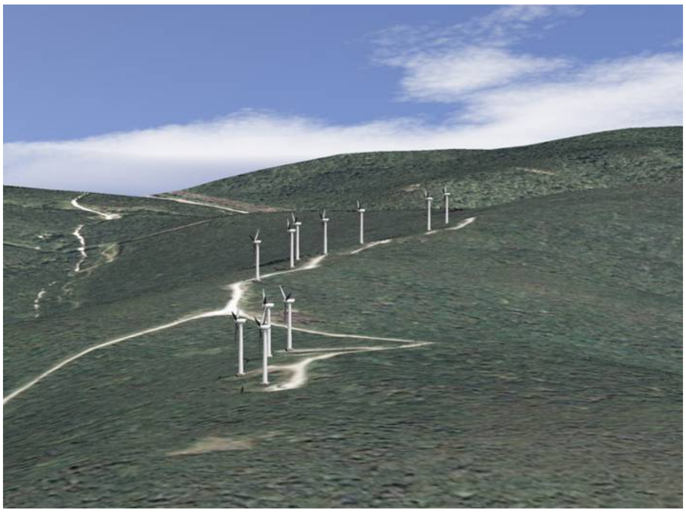

Fig 11 - Searsburg Wind Towers terrain integration

Fig 12 - Butler Farms site

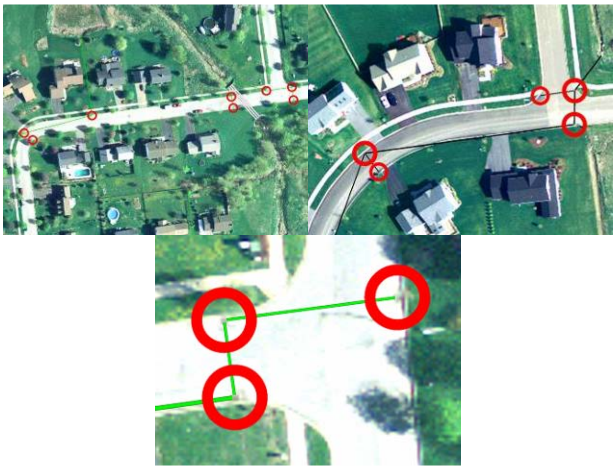

Fig 13 - Butler Farms Storm Water Draining System Positioning

3.3 Restitution Model

3.3.1 Underlying problems

With the constant evolution of spatial data acquisition techniques, digital models embed less and less intelligent information, and put the precision and quantity of discrete information before sophistication of geometric digital models. Restitution of information in 3D is essentially a visual and superficial operation, and, within these limits, offers to certain users a satisfying scenographic conformity. If remarkable progress is taking place in the constitution or the exploitation of photographic databases or point clouds, for instance extracted from LIDAR acquisition, it is not the case for further phases of geometric processing. Such phases extract and recognize forms and spatial relationships, then memorize them digitally from mathematical equations.
This difficulty to automatically extract the original semantics of buildings or cities geometric composition rules is a major obstacle to the constitution of high level geometric and topologic databases, from two-dimensional projections in space (Photography) or 0-dimensional points in space (LIDAR). Nevertheless, numerous advantages can be found in exploiting and extending metrophotography applied to architecture (Deneux H., 1930). In doing so, the metrophotographer, whether being engineer or architect, reconstitutes the volumic or structural logic for the building, as well as its metrics. In the context of a new volumic metrophotography, the deductive steps, oriented towards interpreting the nature and combination of forms, then turns essential, angular and distances measures becoming secondary. If classic photogrammetry relies on inverse perspective techniques, applying retroanalysis to find a building volumic sequencing rather relies on inverse descriptive geometry, topology and logic.

3.3.2 A transitory, hybrid strategy

In the context of the Virtual Vermont project, we had to compose with a certain number of external 0-dimensional data, essentially extracted from digital terrain models (DTM), and external 2-dimensional data, extracted from the photomodelisation of Burlington International Airport.
Surfacic DTM to volumic DTM has been operated through automated processing, using interpolation and approximation algorithms based on third and fourth degree algebraic surfaces. This first step, of purely numeric nature, had for objective to produce a simplified representation of Vermont topography and hydrologic network, in the form of a mathematical description allowing underground geological modeling. In the long term, it enables simulating cuts/fills operations, which are the fundamental basis for transport infrastructure or underground networks planning. Providing volumic improvement on a DTM level of detail is possible, introducing progressive refinement, especially during urban or transportation infrastructure integration. It is not the case when improving photomodels, which have to be replaced with volumic models relative to building design and construction.
Applied polynomial terrain processing principles are further detailed in (Rotgé J.-F., Farret J., 2007).

4. CONCLUSION

The two diagrams (Fig 15) present the general principles of the Virtual Vermont project. In its current stage, it integrates information in an original simulation system, presenting a number of advantages.
Hyperlarge simulation data management, compactness: Information is stored using a specific description format, thus enabling drastic compression levels.
This structural compression, depending on the context, can raise to ratios as low as 1:100 000 when compared to polygonal systems.
Exact precision, perennial reference data repository: 3D solid datasets is stored in its mathematical form, with an exact management of surfaces and volumes (Such as urban underground infrastructures).
Based on such characteristics, the system proposes a reference data model, perfectly valid over time. It enables addressing hardware evolution without the obligation of renewed data acquisition and modeling.
System integration, data import / export: Due to import capabilities and semi automated modeling tools, proposed system enables conversion of existing data in specific formats, and makes use of urban, GIS, and AEC data and systems already available.
The system also produces conventional 3D data, thus enabling interoperability with legacy real time simulation and analysis systems, autostereoscopic display devices, rapid prototyping systems, Internet / Web services such as Google Earth, etc...

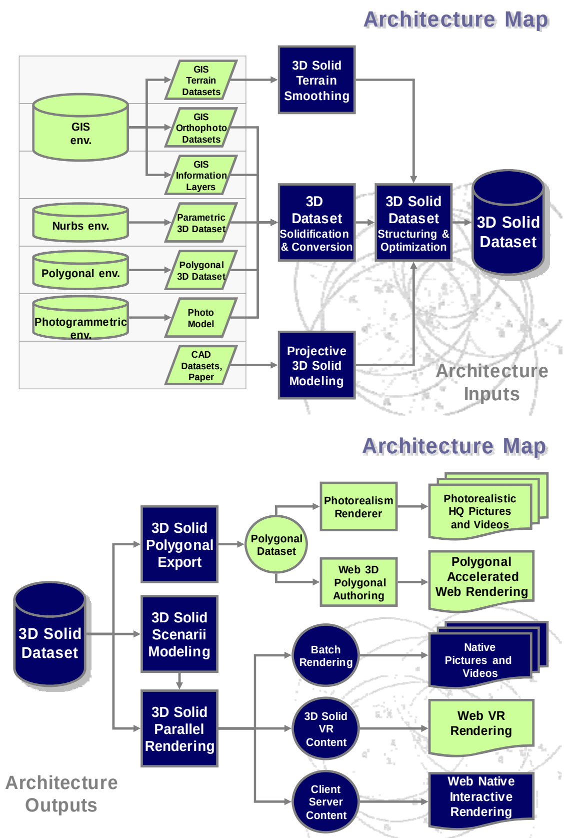

Fig 14 - Architecture Map for Vermont Urban and Rural Heritage 3D Modeling

Parallel Computing Resources: Due to its original design, the proposed approach can make optimal use of parallel architectures, multicore processors, High Performance Computing (HPC) or super-calculators. This enables intensive computation or high availability requirements, such as public access to large heterogeneous reference models.
Real time access: Proposed 3D solid datasets introduce an optimized organisation for data and processes. This organisation enables customized, real time access to large volumes of data. Information is thus made available on demand to urban communities at large, adapting to applicative contexts from public setups to mobile phones or web browsers.
Embedded / mobile, Web services: Proposed 3D solid dataset is compatible with a wide range of applications and information access modalities. In the case of web services, proposed components support a wide panel of configurations, from downloading and interpretation of data fully performed on the client side, to lightweight client solutions which rely on server side computations. Ongoing convergence between web services and mobile client applications also enable to fully support the second type of devices.

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