TOWARDS TO A HYBRID MODEL-MAKING METHOD BASED ON
TRANSLATIONS BETWEEN PHYSICAL AND DIGITAL MODELS

A case study of the freeform architectural design

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Abstract. The extensive applications of digital models might decrease
the capacity of physical model-making for perceptual thinking and
enlarge the gap between architects and physical space with limited visual
experience. This study aims to propose a reverse process for realizing
translations between physical and digital model-making methods from
which architects could maximize their initial ideas in conceptual design
while allowing for rational digitalization in the detailed design. A
review of Reverse Engineering architectural applications is presented
and the hybrid method is proposed and examined in a freeform design
case. The research shows that in the first translation phase, from
handmade physical models to parametric digital models, freeform
graphy could be better parameterized in a low degree of deformation
based on photogrammetry. Meanwhile, in the second translation
phase, from detailed digital models to large-scale physical models,
the digitally-driven fabrication could be applied more precisely and
automatically based on error handling by 3D laser scanning. Moreover,
the process and algorithms developed for the hybrid model-making
method indicate the possibility of being applied to further freeform
architectural design cases.

Keywords. Physical models; Digital models; RE technologies;
Freeform design; Accuracy.

1. Introduction
In the last decade, the emerging practice of freeform architectural design has
become a worldwide blossoming in the field of contemporary architecture. These
imposing buildings re-shape the skylines of major metropolitan cities with a
consistent exploration of dazzling exteriors and striking structures. As the key
to realizing the complexity of building forms or geometries, digital technologies,
are thus becoming the most commonly used methods for current design and
fabrication. It is evident that the digital-oriented design process increases the
productivity and accuracy of freeform generation and manipulation as opposed

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to traditional manual approaches (Aish 2005). But the extensive applications of
digital models might significantly decrease the capacity of physical model-making
for architects and enlarge the gap between virtual and real spatial experience.

Rather than manipulating "flat" surfaces on a computer screen, Frank Gehry,
the pioneer architect who is well-known for his geometric complexity, preferred
to achieve conceptual design by making physical models and drawing sketches
(Isenberg and Gehry 2009). Architects could get access to the direct manipulation
of physical variables like material properties through handmade physical models,
whereas digital models create a distance between architects' perceptual thinking
and objects. As conceived by Arnheim (1969), good perceptions that we read from
the object play an active role on the building of cognition and trigger inherently
creative, freeform thoughts, a critical goal of a design process. Being concerned
with the necessity for human tactile and sensory that assist producing desired
aesthetic and spatial effects, architectural forms are too complicated to be reduced
to solely parameters or logical algorithm as digital models represent. To avoid
the over-reliance on rational digitalization, architects should regard the rising
complexity of perceptive oriented criteria as their approach.

In Gehry's design process, the physicality of models maintains its prominent
identity for possibilities of unexpected conception; at the meantime, the adaption
of digital models further exploits the potentiality of these material constructions,
exhibiting a close interrelation between digital and physical realm (McCullough
1998). From this perspective, the understanding of realizing translations between
physical and digital models to utilize the full potential of perceptual and rational
thinking at the conceptual and detailed level is of utmost concern to architects.
Previous researches on architectural modeling have often been reported from
digital to physical, especially the application of the digitally-driven fabrication
process, such as CNC milling, 3D printing and robotic technologies (Dunn 2012).
However, making large-scale physical models for design thinking and presentation
always has manufacturing and fabrication errors just like actual construction. As
to researches from physical to digital, which enables digital representations of
geometry, always focus on technical applications of Reverse Engineering (RE)
devices. Outcomes of 3D reconstruction like mesh and point cloud models are
non-parametric and could not be used for detailed design directly (Austin 2016).

To solve these two problems and develop an iterative hybrid method, this paper
introduces an updated framework that realizes the translations between physical
and digital model-making methods through RE technologies and algorithm
development. First of all, the study presents a review of architectural reverse
methods and examines the boundaries of these existing methods. Secondly, the
proposed reverse framework is applied to a case study of the curvaceous freeform
surface design. Thirdly, the outcomes and core characteristics of the progress are
discussed prior to the final conclusion.

2. Literature review of RE technologies in architectural design
Reverse Engineering, also called Back Engineering, is the process of extracting
knowledge or design information from a product and reproducing it or anything
based on the obtained information (Eilam and Eldad 2012). Schmitzberger called architectural applications of RE through analysis of its structure, function, and operation as Architectural Reverse Engineering (Schmitzberger 2007). It’s widely used in field survey, early conceptual design development (Nir and Capeluto 2005), construction site monitoring, as-built documents (Shih and Wu 2005), augmented reality (AR) and mixed reality (MR), and architectural heritage conservation (Loannidis et al. 2015), etc.

In the 1980s, Frank Gehry started to apply contact RE technologies in the early architectural reverse process to digitize physical models. With the increasingly difficult task of describing complex geometries, architects scanned the sizeable physical model by using RE devices and imported the digital outcome into CATIA for 3D reconstruction (Lindsey 2001). Digital models allowed Gehry to realize different analysis and detailed design. It also allowed his design team to carry out changes and evaluate them immediately in terms of feasibility and costing.

Nowadays, non-contact RE techniques mainly consist of multiple technologies including passive and active, range-based and image-based methods (Mateus and Ferreira, 2013). Among these techniques, photogrammetry and 3D laser scanning are the two major categories of reverse engineering widely applied in architectural applications. They could bring us with a new vision of cognition and understanding of architecture through the exploitation and manipulation of these data, not just in a practical way for surveying and modeling accurately and rapidly.

3. Methodologies

3.1. PHOTOGRAMMETRY

Photogrammetry is a kind of passive image-based RE technique which depends on a group of 2D images of the target to generate a 3D model. The emphasis of photogrammetry is taking proper photos in the data acquisition step. The quality and accuracy of 3D reconstruction depend on shooting angles, shooting positions, the number and the quality of photos. These factors are decided by the ability of spatial cognition to the target and the application experience of photogrammetry. The key is that the group of images should be taken with multiple angles covering the whole target with proper numbers and overlap rate.

Main steps in photogrammetry software are automated or semi-automated such as images matching and stitching, visual feature point extraction, structure positions calculation and optimization, camera distortion calibration, point cloud densification, and meshes generation (Mateus and Ferreira 2013), etc.

3.2. 3D LASER SCANNING

3D laser scanning is a kind of active range-based RE technique which emits light and detects its reflection passing through an object to probe a target. According to principles, 3D laser scanning can be classified as time-of-flight, phase-based, Simultaneous Localization and Mapping, and triangulation, etc. The essential difference among these categories are the various mechanisms of laser generation and principles for calculating the distance from the sensor to object.
In data processing, 3D laser scanners have the bundled software of RE devices for point clouds processing and analysis. This procedure depends on the selected software but still can be summarized as the main steps including registration, image projection, orientation, segmentation, and sampling, etc.

3.3. THE EXPERIMENTAL PROCESS OF TWO TRANSLATIONS

The process includes two translations to solve the two problems mentioned above respectively. Translation 1 is the process from the handmade physical model with perceptual design to the parametric digital model for detailed design. Photogrammetry is appropriate to reverse the small-scale physical model for a medium-definition purpose. Translation 2 is the process from the detailed digital model with rational digitization to the large-scale physical model for further design thinking. 3D laser scanning is used to get the high-definition point cloud model of the structure physical model to update the original skin digital model. The capability of the integrated application of RE devices and software is adequately demonstrated. The final specific geometry and the large physical model are not the ultimate goals. Instead, the reverse process and algorithms developed for the hybrid method are critical points of this research.

4. Results and discussions

4.1. TRANSLATION 1: FROM PHYSICAL TO DIGITAL

4.1.1. Step 1: Physical model-making

The case study performs a freeform shape with a smooth upper surface as the skin and a multiple spherical lower surface as the structure (see Figure 1). Modeling clay is used for making the freeform model so that architects can make full use of their perceptual creativities depending on the feeling of aesthetic form. For better reverse by photogrammetry in the next step, the skin and structure forms are made in two physical models separately.

![Figure 1. Physical models of the freeform surface design.](image)

4.1.2. Step 2: From the physical model to mesh digital model

In this reverse step by photogrammetry, a mirrorless digital camera, Canon M6 with a 22mm prime lens, is used to make data acquisition. The data processing step uses Autodesk Remake to convert photos into 3D meshes. The size and complexity of the physical model decide the number of shooting. The research tries different groups of shooting angles, shooting positions and image qualities to gain the mesh
model in excellent condition with the least amount of photos. Finally, 85 photos of the upper surface and 147 photos of the lower surface in 6000×4000 resolution are taken, and Remake is used to generate the mesh model with no damage parts in appearance (see Figure 2). The study takes photos in three complete laps with vertical shooting angles of 25, 50, 75 degrees. The overlap rate of every two photos is more than 70%. The original mesh model with thousands of triangular meshes has a severe influence on the computing efficiency in Dynamo. Simplification is necessary before the next step of parameterization.

Figure 2. From the physical model to mesh digital model by photogrammetry.

4.1.3. Step 3: From the mesh model to parametric model

The critical step in Translation 1 is the parameterization and rationalization of the freeform curved surface. The upper surface serves as an example to illustrate this and next steps. A surface parameterization algorithm is developed based on Dynamo. NURBS curves are generated by projecting gridlines to the simplified mesh model. Then lofting is used to create the NurbsSurface which can be adjusted and detailed by the manipulation of splines and control points (see Figure 3). The gridline density in BoundingBox controls the accuracy of Translation 1 as the number of triangular meshes does. A checking step is designed to calculate the level of similarity in the next step. If the outcome meets the demand of the reverse accuracy, the parametric digital model can be determined, or parameter setting of meshes and gridlines should be modified to restart the parameterization step.

Figure 3. Generation of the parametric digital model.

4.1.4. Step 4: Similarity comparison

Although the reductions in triangular meshes and gridlines in BoundingBox decrease the computing speed of the parameterization algorithm, they will lead to the deformation and decrease the accuracy of Translation 1. The study develops a similarity analysis algorithm for this checking step. The algorithm is based on
a differential method and uses the color display to express levels of similarity between the original mesh model and parametric digital models generated by simplified mesh models. The research chooses eight simplified mesh models whose numbers of meshes in each are in an array from 50 to 400 in increments of 50, and tries 10, 20, 30 gridlines to generate parametric digital models respectively. A total of 24 parametric models are compared with the original mesh model. The yellow part represents the maximum level of similarity. The darkening of the red and blue demonstrates the increasing of the deviation value in positive and negative directions respectively (see Figure 4). The most substantial deformation exists in the surface of maximum curvature variation. The deformation rate is negatively correlating with the number of triangular meshes and gridlines. When the number of triangular meshes goes up from 300 to 400, the rate of deformation decreases slowly and is less than 0.5%. Under the circumstances, the deformation rate is nearly the same when the gridline is 20 and 30 (see Figure 5). In consideration of both precision and computing speed, the research chooses the simplified mesh model with 300 triangular meshes and sets the parameter of 20 gridlines to have the final parametric digital model for detailed design.

4.2. DETAILED DESIGN OF THE STRUCTURE AND SKIN

The detailed design is a process of rational digitization. After optimizing to smooth both the upper and lower surfaces by adjusting splines and control points...
of the parametric model, the structure and skin digital models are created by the generation algorithm which is developed based on analytic geometry methods (see Figure 6). Since the rule of the specific form is controlled by parameters and formulas, architects’ abilities of rational thinking can be useful to this kind of architectural freeform generation.

Figure 6. Structure and skin digital models.

4.3. TRANSLATION 2: FROM DIGITAL TO PHYSICAL
4.3.1. Step 1: The manufacturing and fabrication of the structure physical model
The process in Translation 2 focuses on manufacturing and fabrication (see Figure 7). The final physical model for design presentation is in length of 2.1m and width of 1.2m. To facilitate the manufacturing of the large-scale physical model, the research develops a series of algorithms for manufacturing information output. CNC cutting outlines of structure and skin components are generated with serial numbers in order. They are arranged in the same plane of MDF boards based on the automatic adjustment of UV Coordinate Systems. All the manufacturing information can be exported to SAT files for CNC cutting. The research designs a series of snap joints to fix skin components including panel and glass to the structure model. The sizes of the snap joints are 3mm in this case which is decided by the thickness of MDF boards and the diameter of CNC drill. After the manufacturing and fabrication work of the structural physical model, the generation of deformation and deviation has been perceived.

Figure 7. The manufacturing and fabrication of the structure physical model.
4.3.2. Step 2: From the physical model to point cloud model

Since the design of snap joints only allows an error of 3mm between structure and skin physical models, the skin digital model should be updated according to the structure physical model with deformation. 3D laser scanning is applied to do reverse work (see Figure 8). The research uses ZScanner 700 CX, a handheld laser scanner to make data acquisition, and pastes the dot targets to critical positions of the structure physical model for positioning of scanning. These positions are installation locations of skin components. After the scanning work, a 3D point cloud model is generated by ZScan which contains all the geometry and position information of the structure physical model. It is used to do deformation analysis and to update the original skin digital model to fit the structure part.

![Handheld laser scanner, dot targets on key positions of the structure model, Generation of the 3D point cloud model](image)

Figure 8. From the physical model to point cloud model by 3D laser scanning.

4.3.3. Step 3: The deformation analysis and feedback

This step provides the feedback of deviation values between digital and physical structure models. The research chooses 102 key points which are triangular vertexes of skin panels to do deformation analysis (see Figure 9). 35.30% of deviation values arrange at 0-3 mm which meet the error requirement of snap joints. On the contrary, 64.70% of key points couldn’t. The maximum deviation value of the single point is 43 mm which is shown in the red dashed box. The yellow dashed box indicates the principal errors of consecutive points. Physical shape changes because of the manufacturing and fabrication methods, as well as its gravity and conjunctions of different materials, etc. cause these errors.

![The deviation values between the digital and physical structure model](image)

Figure 9. The deviation values between the digital and physical structure model.

4.3.4. Step 4: Updating the digital skin model and final fabrication

The research develops the algorithm to update the skin digital model based on deformation feedback. The comparison of key point positions between digital and
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Point cloud models of the structure is the first step to do position matching. After list sorting generates the new sequence, new key points replace the original ones to realize the updating. Meanwhile manufacturing information output of the skin part can be generated automatically by algorithms just as the last step. After the manufacturing process of the skin part, skin components including MDF panels and perspex glasses can be installed to the structure physical model accurately (see Figure 10). The outcome demonstrates the necessity of reverse work.

Figure 10. The Final physical model of the freeform Curved Surface.

The research in translation 1 aims to solve the problem of translating the intuitive design thinking explicitly into the editable digital model for detailing. Translation 2 concentrates on manufacturing and fabrication errors of the large-scale physical model for further design and presentation. RE technologies for architectural applications, like photogrammetry and 3D laser scanning, are the critical methods of the integrated experimental process (see Figure 11). Five kinds of algorithms including the parametrization of the freeform surface, similarity analysis for simplification and parametrization, generative design for detailing, manufacturing information output and automatic updating of digital model are developed for this reverse workflow to realize the whole process automatically.

Figure 11. Summarization of the integrated experimental process.
5. Conclusion and future work

To maximize architects’ abilities of perceptual thinking in conceptual design and rational digitalization in detailed design, this paper explores an experimental process of translations between physical and digital model-making methods. It demonstrates the capability, necessity, high precision and high efficiency of this workflow for the freeform architectural design. The application of RE technologies in conjunction with algorithm development enables an iterative hybrid method to optimize the reverse design workflow. The process and algorithms as the research outputs could be applied to similar design conditions.

Applications of this workflow in actual building cases can embody the values of this hybrid method. The future research will continue to develop the process and algorithms based on real building and enhance the level of automation. Meanwhile this method currently only fits for the given type of complex geometry composition as a freeform curved surface. It needs to be tested on cases of other geometry types to achieve a robust validation for future universal applications.

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