Targeted Reverse Engineering Techniques for Generating Architectural Solid Models for Additive Manufacturing Fabrication

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ABSTRACT

Additive manufacturing (AM) technologies enable designers to readily fabricate a physical model of a complex free form object; however, a 'water tight' model is required for effective fabrication. To create the CAD model for a classical building that has limited relevant structural information, reverse engineering techniques must be applied. Using digital images, similarity and pattern analyses, a full solid model of key exterior and interior features was generated in a systematic manner for manufacture using the 3D Printing process. Feature geometry consisted of lines, arcs, extruded, swept, and revolved solids. Design redundancies were leveraged to ignore noise due to the data collection or building variations. 3D Printing technology specific constraints needed to be addressed, such as altering wall thicknesses for appropriate model strength, and providing assembly interfaces to allow for ease of assembly and disassembly. This approach is most appropriate for buildings that do not contain complex free form geometry, and is illustrated using a case study: Assumption University in Windsor, which was founded in 1857 and is administered by the Congregation of St. Basil.

Keywords: reverse engineering, architectural replica model, 3D printing.
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1 INTRODUCTION

Physical architectural scale models are used for evaluation and display purposes. When using traditional machining methods, much time is spent on process planning, fabrication and assembly. This process can be streamlined using additive manufacturing (AM) methods such as 3D Printing (3DP). AM fabrication consists of additive, tool-less processes that are capable of producing complex geometries with minimal human intervention. A three dimensional (3D) part is developed from layering two dimensional cross sections successively to create the final solid. Undercuts, free form geometry, and blind features are manufactured "easily", especially compared to traditional machining processes. For the 3DP process, layers of powder are deposited and spread evenly, and the cross section is formed by applying binder via an inkjet printing head. 3DP allows for color to be applied to any surface or tessellated facet on the model.

When creating a scaled architectural model, the characteristics of the form, structure, and visibility with respect to distinctive attributes need to be considered. For AM, another key requirement is having a water tight 3D part to be converted into the file format supported by the AM process. Typically this is an STL (Stereolithography Tessellation Language) file. The STL format represents 3D models as a set of triangular facets. For older buildings, there usually is no CAD model, and there may be no reference blue prints, or they contain obsolete information. Hence, reverse engineering (RE) techniques need to be performed to generate a valid CAD model. Here, RE refers to the process of creating a 3D geometric model from a physical object. This in essence is not RE, as this includes collecting information on materials, surface treatments, etc., but reverse form modeling, which is a fundamental building block of the RE process. Digitizing the 3D shape from an object is utilized in many fields, including:

- The reconstruction of mechanical components [7], [8], [18], [21],
- Documenting and/or measuring cultural objects (sculpture or other artwork) or artifacts in archaeology, paleontology and other scientific fields [13], [19], and
- 3D reconstruction of architectural buildings, which is the focus of this research [6], [11], [14-17], [20].

This is list is not exhaustive, and there are data collection and associated modeling challenges in each field. The customary process used for reverse engineering is illustrated in Fig. 1. There are five major steps: metrology planning, data acquisition, pre-processing, surface construction, and creating the final CAD model. First, the characteristics that are to be captured need to be established. The size, form, physical characteristics (i.e. reflectivity of the surface), tolerances and so forth will influence the data collection tools, and the measurement strategy. For digital data collection, many RE applications utilize a tactile probe or non-contact data acquisition scanner. Data collected from tactile probes on a CMM is very accurate, but the data collection process is slow. Conversely, for non-contact scanning systems, such as a laser scanner, large volumes of data can be collected quickly. The 3D laser scanning tools leverage mathematical relations between the direction of the emitted laser beam and the direction of the detected reflection to generate information on the position of the object surface points. Unfortunately, these systems are hampered by reflections, scatter due to sharp edges, and reflective and transparent materials. Hand tools, gage blocks, etc. may also be used for data collection, but they may be sensitive to the user skill levels.

In several architectural RE endeavors, the data collection tools have consisted of surveying tools, 3D laser scanners, laser time of flight scanners, and digital photogrammetry [6], [14], [15], [17]. Time of flight scanners measure the delay between emission and detection of light reflected by a surface using the known value of the speed of light in air. Digital images are used to collect textures to complement laser scanned data [6], or may also be the data collection source [17]. The CMM based and laser scanning systems are not inexpensive and each system has unique decision making and analysis challenges associated with the data collection, processing and CAD model reconstruction.

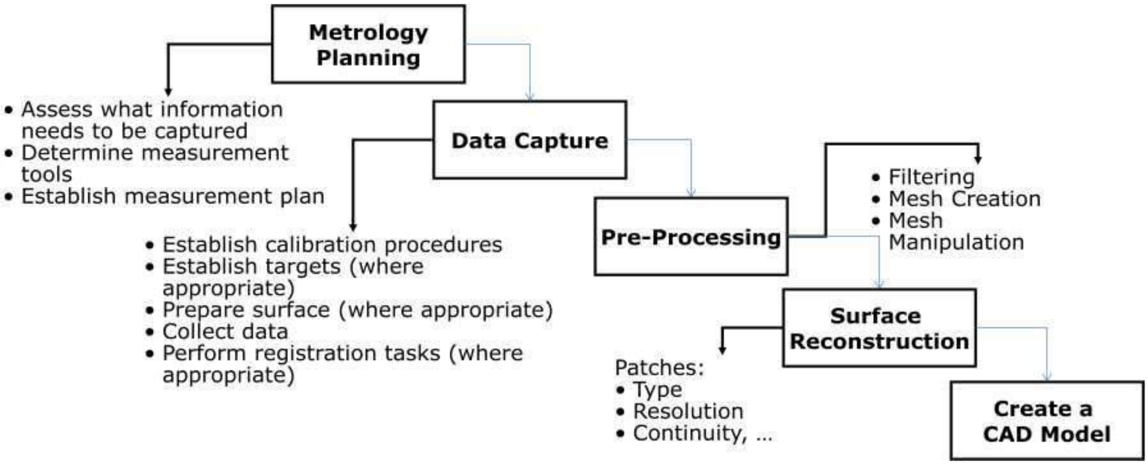

Fig. 1: Standard process flow for reverse engineering.

Prior to collecting data, the system must be calibrated. Due to size or accessibility issues, not all the data may be collected in one set up. Hence, physically adding target objects or selecting target features may be necessary to assist in effective merging of multiple sources of data. Multiple views of an object are necessary to ensure that there is a digital coordinate representation for all the surface features (Fig. 2). To capture this information, either the data acquisition scanner or the part must move; hence, the resulting point cloud coordinate data is relative to the new view position. Registration is the process whereby these multiple views are aligned into a single global frame as each scan has its own local coordinate system. [2-4].

When working with point cloud data from a laser scanner or a digital image, the data must be filtered to reduce noise and the decrease the number of data points to improve processing times. From the filtered data, sophisticated algorithms are utilized to generate a surface model, either directly from the point cloud data, or after creating in intermediary surface mesh (which contains no topological information). These surfaces are fit together independently; hence, any relationship between the surfaces and other geometric entities, such as orthogonality, will not exist. Beautification techniques, which aim to improve the model so that it exhibits exact geometric regularities, may used to identify primitives, detect similarities and symmetry, curvature estimation and so forth [6], [12]. However, artifact based errors (i.e., worn features) as well as numerical errors are imbedded in the model. Consequently, the quality of the reconstruction not only depends on the number and density of the sample points but also skill level of the user creating the final model [6], [20].

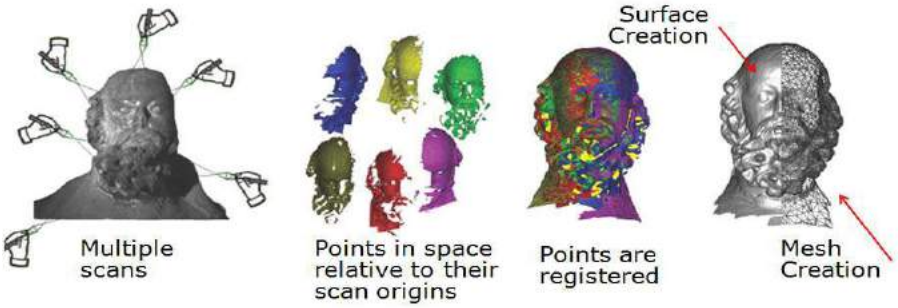

Fig. 2: (a) Multiple scans, (b) point cloud data, (c) registration and (d) surface generation for a sculpture adapted from [10].

In order to create an architectural building solid model for subsequent fabrication of a scale replica using AM, a different approach is required for the data collection and model reconstruction. Feature geometry should consist of lines and arcs that can be used to create extruded, revolved, or swept geometry. Consider the stamped panel (Fig. 3), which can be contained in a 310 x 162 x 28 mm bounding box. 112847 points were collected using the Metris® LC50 laser scanner mounted on DEA CMM (after this part was coated with a non-reflective white powder). When reconstructing this component, significantly less geometric elements are required to create the line and arc primitives required to describe the component fully. This geometry is used to create the surfaces (in this example) in the final model. The ideal geometric shape constraints are used. Much extraneous data is captured with the non-contact scanning system, which is discarded during the model recreation process. For a large building, the data collection and management challenges are more extensive.

Specific patterns and design redundancies need to be captured. The user should be able to easily modify the geometry based on new design or manufacturing constraints. The model should be 'water tight', so that a scale model can be built using the 3DP process.

(a)

(b)

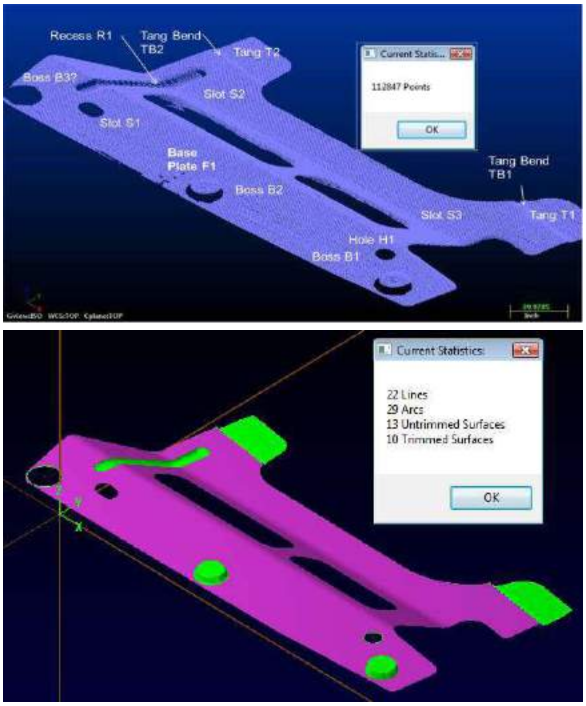

Fig. 3: (a) Stamped panel reconstruction points and (b) final geometry.

The goal of this research was to develop a methodology to construct an ideal geometric model that captures the key design characteristics and intended geometric regularities for a classical building, which the designer can readily evaluate and modify, while:

- Minimizing the data collection costs, the amount of data collected, and the data processing;
- Identifying, extracting or ignoring (if necessary) irregularities, and
- Leveraging the color printing capabilities with the 3DP process.

The approach is illustrated using a case study: Assumption University in Windsor (Fig. 4), which was founded in 1857 and is administered by the Congregation of St. Basil [1].

Fig. 4: Assumption University.

2 THE PROPOSED ARCHITECTURAL RECONSTRUCTION APPROACH

For the architectural reconstruction challenge, a modified RE process, illustrated in Fig. 5, was developed and utilized. As the creation of a scale model replica is the final application, this impacted the process methodology and rules. The reconstruction methodology described here in section 2 follows this process flow.

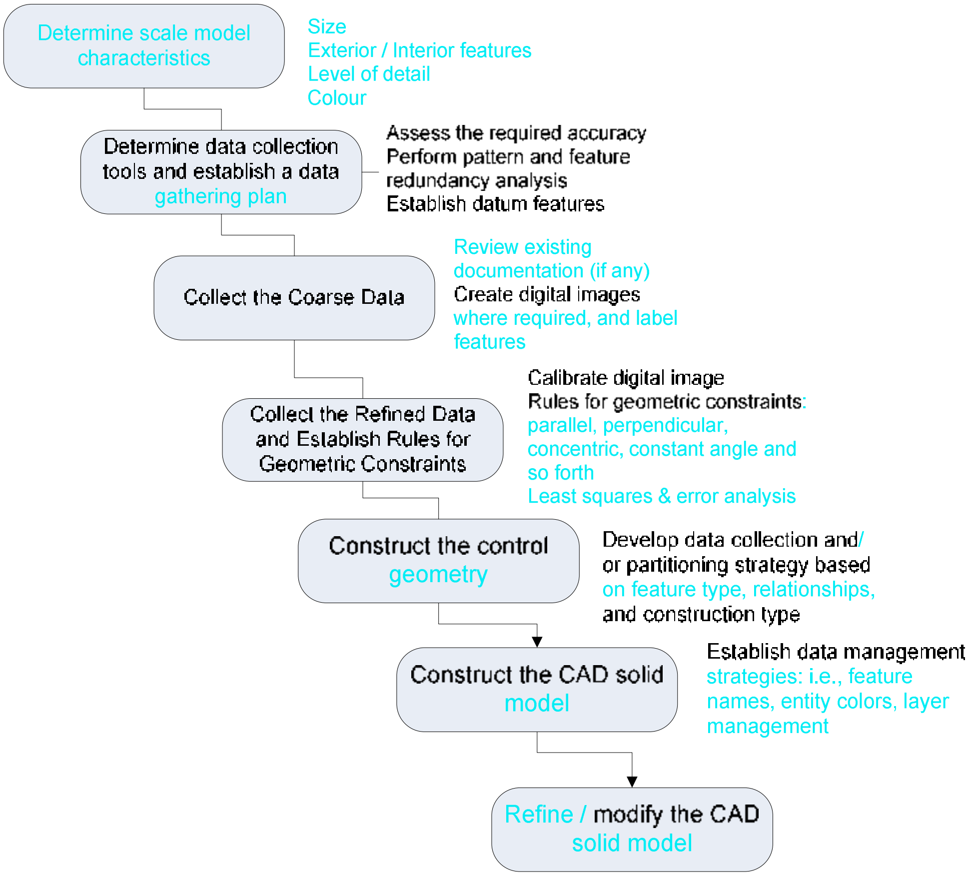

Fig. 5: Process flow for reverse engineering an architectural building.

2.1 Model Characteristics

The basic characteristics of the model replica were determined while considering the 3DP capabilities. The scale model is to have a maximum length of 24 inches (0.6 m). The building itself is 250 ft x 130 ft or 76 x 39.7 m (Fig. 6). Therefore the scale factor is 125:1. There was to be 'general accuracy' reflecting the building exterior. The minimum feature size that can be realized on the model is 0.006 inches (0.15 mm) based on the 3DP system being used (Tab. 1), which corresponds as is 0.75 inches (19 mm) at full scale. There are no up to date blue prints on file, the available prints are dated 1950 and there have been building modifications; hence, the proper exterior and interior boundaries need to be established. The colors of the model were to be the same as original color of building. The brick at the front entrance was the original brick color. Soot deposits have changed the brick color on the other building surfaces. There was to be an emphasis on the interior and exterior chapel areas, and extra decorative features, such as window details, the organ, and the steeple (Fig. 7). The decorative features may not be to scale for effective visualization.

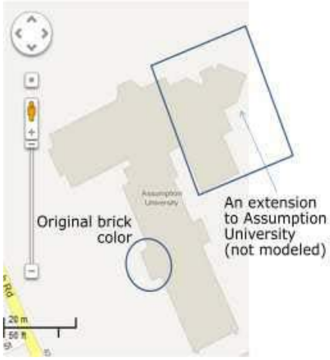

Fig. 6: Assumption University footprint [9].

Feature	Parameters
Color	180,000 colors (2 print heads)
Resolution	300 x 450 dpi
Minimum Feature Size	0.006 inches (0.15 mm)
Build Size	8 x 10 x 8 inches (203 x 254 x 203 mm)
Layer Thickness	0.0035 - 0.004 inches (0.089 - 0.102 mm)

Tab. 1: ZPrinter® 450 process characteristics [22].

Fig. 7: Key Assumption University architectural features [1].

2.2 Data Collection Tools and Data Gathering Plan

A formalized, systematic approach was made to assess the Assumption University building's features and their characteristics. The feature types, their physical relationships, and the geometric construction techniques required to recreate the features needed to be determined, as this impacted the data collection tools and the data collection plan. The key features and their characteristics are summarized in Tab. 2.

Most geometric relationships, and the repetitive features and patterns, are readily evident when reviewing the digital images or evaluating the building directly. For example, on the first floor there are 42 windows and 6 different window styles. The window types are clustered. There are geometric constraints evident with respect to profile curve offsets, orthogonality, alignment, constant spacing, and mirroring around a vertical line (Fig. 8). There are several elements within the windows themselves; however, geometric constraints with respect to symmetry, perpendicularity, parallelism, and constant curvature are apparent and should be incorporated for an ideal representation.

Upon evaluating the key features and it was determined that majority of the 3D construction can be performed using extrusions from base geometry and Boolean operations. Once a reference feature is created, the subsequent operations consist of transformation processes. The base geometry typically consists of line and arc primitive geometry with unsophisticated geometric relationships. The column capitals, and the chapel ceiling lamp supports are an exception to this (bolded text in Tab. 2). Surface reconstruction techniques are required for these features. However, at a 125:1 scale factor, the detail would be lost; hence, it was decided to exclude these features.

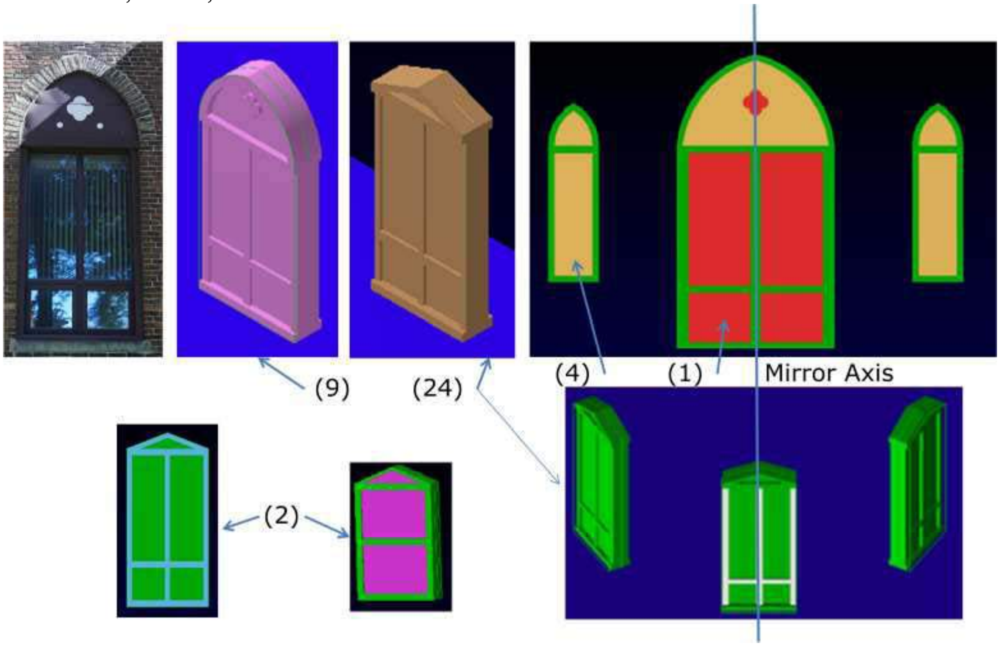

Fig. 8: 1st floor window styles, and the quantity per type.

As the majority of features can be created using extrusions, trimmed planes or swept geometry, a hybrid technique using manual data collection with tapes, and photogrammetry is employed here. A Sony SLR - Digital Camera (DSLR-A550) is used to collect digital images with a tape measure for calibration and base line reference purposes. Google Maps (satellite and street view) is also utilized for geometry relation assessment [9].

Feature Type	Physical Relationships	Construction Approach
Building outline	Planar faces (majority orthogonal)	Create profile (lines) Offset profile the desired wall thickness Extrude
Outside corner pillars	Planar faces Pillars are orthogonal at edges Pillars are parallel to each other, equally spaced, and abut onto the walls	Create profile (lines) Extrude
Office windows	Offset planar faces: frame, lintel, etc. Decorative features Feature geometry is perpendicular and , parallel, with symmetric elements, mirrored around a vertical axis Common types per floor, clustered in repetitive patterns	Create profile (lines, and arcs) Extrude Boolean subtract window profile from building outline / walls Translate and repeat as required
Chapel windows	Offset planar faces: Curvalinear elements and several decorative features Feature geometry is symmetric, with concentric and tangent elements, mirrored around a vertical axis	Create profile (lines, and arcs) Extrude or sweep Boolean subtract window profile from building outline / walls Translate and repeat as required
Chapel organ	Planar faces	Create profile (lines) per pipe Extrude
Chapel columns	Column: Tapered cylinder Capital: Complex surface geometry – symmetric, repetitive elements	Create profile (circles) Extrude Point cloud data to determine critical wireframe geometry for surface reconstruction
Chapel ceiling	Gothic cathedral arches	Create block Create arch profiles Extrude (cut) Translate and repeat as required
Chapel ceiling arch edges Chapel lamp supports	Complex mould profile edge Complex surface geometry – symmetric, repetitive elements	Create profile (lines, and arcs) Create sweep curves along arch edges and sweep Point cloud data to determine critical wireframe geometry for surface reconstruction
Steeples	Planar faces Repetitive, symmetric	Create block, extruded triangles and trim to control planar faces Create recessed profiles, extrude cut Trim steeples to roof line
Roof ornamentation	Planar faces Repetitive, symmetric	Create profile (lines) Extrude Translate and repeat as required
Doorways	Planar faces	Create outline

		Extrude (cut) Translate and repeat as required
Floors	Planar faces	Use build outline Extrude desired floor thickness
Staircases	Planar faces	Create outline Extrude

Tab. 2: Feature summary.

2.3 Collect the Coarse Data

Digital images were taken along the exterior and interior periphery of the building at different distances in order to either capture detail, or to capture many key features for pattern analysis (Fig. 9). Features were overlapped between images for cross reference purposes. The images and their labels were correlated to their location along the building periphery. To establish a relationship between the pixels dimensions and the physical dimensions, a vertically extended six ft measuring tape (1.83 m) is included in each picture. Physical measurements were also taken for correlation and calibration purposes as distortion is contained within the images.

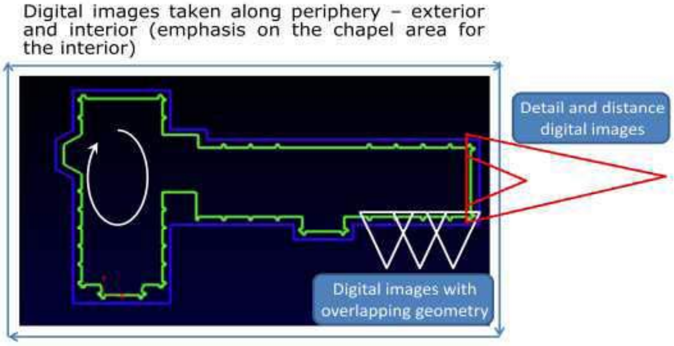

Fig. 9: Digital image data collection.

2.4 Collect the Refined Data and Establish Geometry Reconstruction Rules

Raster based data analysis was first performed in order to establish rules with respect to geometry constraints, to determine curve characteristics, and to perform noise analysis. Raster ‘pixel units’ were used with least squares (LS) analysis for line and arc fitting. Classical least square fitting for a line was initially used for linear geometry, and the algebraic fit (AF) method was utilized for arc geometry.

In Chernov and Lesort [5], fast and non-iterative approximations for a least squares fit for circles are presented. There are three versions of the AF method – the one utilized here minimizes the sum of squares of algebraic distances, and is described below:

$$F_1(a,b,R) = \sum_{i=1}^{n}[(x_i - a)^2 + (y_i - b)^2 - R^2]^2 \tag{2.1}$$

$$F_1(a,b,R) = \sum_{i=1}^{n}(z_i + Bx_i + Cy_i + D)^2 \tag{2.2}$$

Where $z_i = x_i^2 + y_i^2$
$B = -2a,$

$C = -2b$,
$D = a^2 + b^2 - R^2$,
n is the number of data points, and
a is the circle center x coordinate, b is the circle center y coordinate, and R is the circle radius.

Now, differentiating F_i with respect to B,C,D yields a system of linear equations:

$$MxxB + MxyC + MxD = -Mxz \tag{2.3}$$
$$MxyB + MyyC + MyD = -Myz \tag{2.4}$$
$$MxB + MyC + nD = -Mz \tag{2.5}$$

Where $Mxx = \sum x_i^2$, $Mxy = \sum x_i \ y_i$, $Myy = \sum y_i^2$, and so forth.

After solving for *B, C*, and *D*, *a*, *b*, and *R* can be resolved, providing an approximation of the circle geometry for a set of data points.

For the Rose window (Fig. 10), the inner radii for three elements are evaluated using 5 and 10 raster data points using the AF, and compared (Table 3). There is a maximum of 1% difference when using 10 versus 5 data points. When extending to 15 data points, there is no noticeable difference in the radius value when compared to the 10 data points (< 0.1 %). To complete the evaluation process, the circumcircle approach of creating a circle from 3 data points was performed for arc A. 6 unique points from the data set were used to create two arcs. The radii values were 73.86 and 76.15 units, which represents a 3% value difference. There is noise due to shadows, build tolerances, and distortion within the digital image, which impact the raster point selection. Therefore, it was determined to use the AF method and 10 raster data points for each arc to determine its key values.

Label	5 data points (pixel units)	10 data points (pixel units)	Difference (pixel units)	Difference (%)
A	75.67	75.58	0.09	0.12%
B	74.38	75.14	- 0.76	- 1.01%
C	74.54	74.8	- 0.26	- 0.35%
Average	75.02			

Tab. 3: Circle radii comparison for 3 radii for 5 and 10 pixel data points.

Fig. 10: (a) Rose window digital image, (b) wire frame geometry and (c) solid model reconstruction.

LS was initially used for line geometry assessment. In order to avoid the degenerate case that occurs for horizontal and vertical lines, the digital image was rotated, and raster data points selected along linear features for analysis. It was found that the difference in the slope was negligible (within 0.2°) when selecting two end points, or a series of points along the feature. Consequently, it was determined to select end points to perform data analysis.

Using the raster 'pixel units' as a reference, data points were collected and input into a commercial CAD/CAM software package to develop rules for geometry constraints. Exploiting these constraints allows the designer to ignore noise, improves the form reconstruction process, and minimizes the amount of data collection activities. The RE rules are:

- All geometry results from a combination of linear segments or arcs;
- Parallelism, perpendicularity, and orthogonality are assumed when the line segments are within $\pm 2°$;
- Arcs are to be tangent to lines, or other arcs;
- Circles/arcs are considered exactly concentric when the arc centers deviate less than 1 in or 25 mm;
- Feature symmetry will be leveraged wherever is it evident that geometry is mirrored about a control axes;
- Uniform geometry offsets are to be applied wherever it is deemed appropriate; and
- The minimum geometric element to be considered is 3.5" or 89 mm, which results in a 0.028 in or 0.7 mm built feature as the reverse engineered model will be scaled by 125.

To summarize, using the digital image data to create line or arc segments, the original, structured design intent can be readily extracted. Minimal raster data is required: 10 points for arc segments and 2 points for line segments. Conventional CAD tools can be to be used to ensure the geometric constraints are respected, and to create offset geometry for detailed contours. The windows, roof ornaments, and steeple geometry align; hence, there is significant repetition that can be exploited when generating duplicate features.

2.5 Construct the Control Geometry for the Solid Model

The base wire frame geometry needs to be created from the image data; hence, the image data needs to be calibrated to physical data. First, the building outer periphery was created using the existing blue prints as an initial reference. As the blue prints are obsolete, physical measurements were performed to collect data where there was no information, or to confirm dimensions. The data points collected from the digital images were used to complement the information used from the blue prints. When the dimensions were extracted from a digital image, the fully extended 6 ft (1.83 m) scale was used to calibrate the pixel units to physical units using the Pythagorean Theorem and ratios (Fig. 11). The raster coordinate positions were captured from the physical marker points, and the raster 'pixel units' correlated to a known distance. Note: the Y values increase in the downward direction as the *0, 0* reference point is on the upper left hand corner.

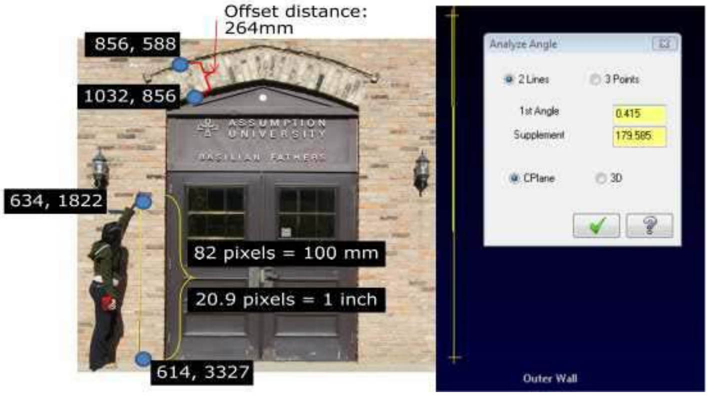

Fig. 11: (a) Digital image, scale, and initial calibration and (b) orientation angle.

When there is an orientation issue with the image, the rotation angle can be readily determined by selecting two raster data points from the curve of interest, and evaluating this line from a horizontal or vertical line. In Fig. 11 (b), the orientation is off by 0.415°.

Upon completion of the exterior periphery, the first floor interior geometry was created. The build wall thickness of the replica model was selected to be 4 mm thick after testing for strength; hence, the interior contours were offset by this distance, and the corridor and office walls created. Then, doors and their frames were drawn. There are 10 door styles; however, 5 door styles are repeated. Therefore once the basic geometry is established, copies can be created at the desired offset distances or mapped around a corner, as necessary (Fig. 12).

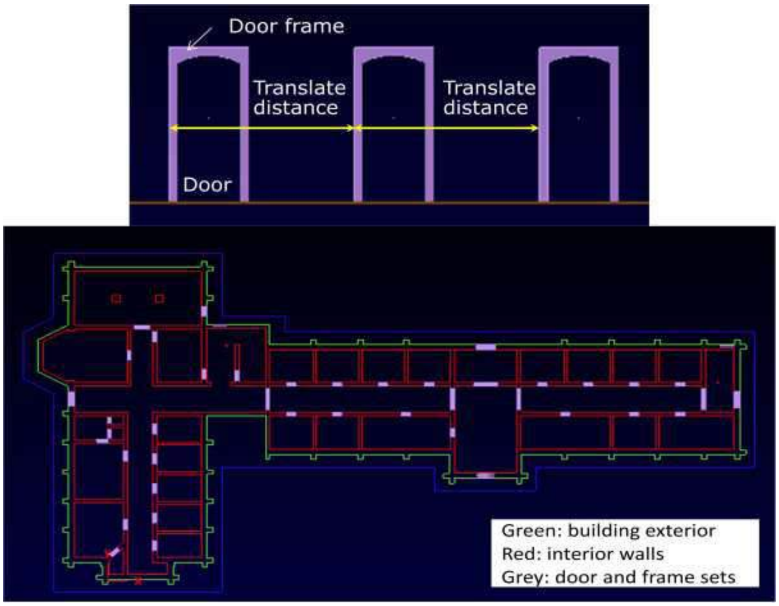

Fig. 12: (a) Door and frame, and (b) first floor base line geometry.

The base geometry of the window is divided into the upper and middle frames, and the lintel. Orthogonality and symmetry are leveraged to create the base window wire frame geometry for the window solid models. Five solid construction operations are used for all the first floor windows: 3 to create the frame, and 2 to allow for decorative printing using the 3DP (Fig. 13). The base geometry was determined by averaging data from at least two windows of the same type (when possible). Using the digital images with overlapping features, the translation vectors were determined for duplication. The completed first floor is illustrated in Fig. 14. The second floor, chapel, roof and steeples were then constructed, in this order.

A slightly different methodology was utilized for the organ model. The picture file was converted from raster to vector data using a conversion module. This converted geometry was used as a reference or template for the final organ geometry as the converted data was noisy. Basic translation and trimming functions were used to create the organ wire frame geometry, and afterwards the scaling factor was applied. This technique can only be used for ‘extruded’ objects where there is crisp feature differentiation. Irrespective of the technique, this work is highly repetitive, and the same method of correlating the raster data to physical dimensions, creating reference geometry from the raster data; applying geometric constraints; and constructing base wireframe geometry for the feature solid model is used for the Rose window (Fig. 10), chapel organ, the chapel windows, and the second floor windows (Fig. 15). Sample translation vectors for mapping duplicate features are illustrated in Fig. 16.

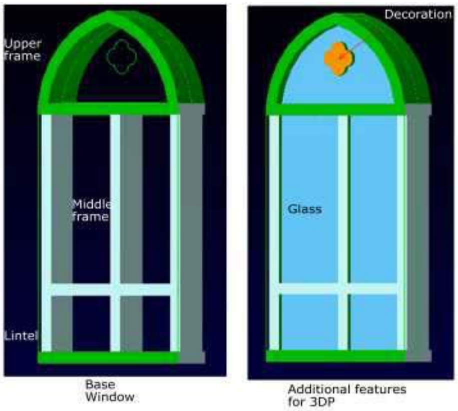

Fig. 13: (a) Window base elements, and (b) Window decorative elements.

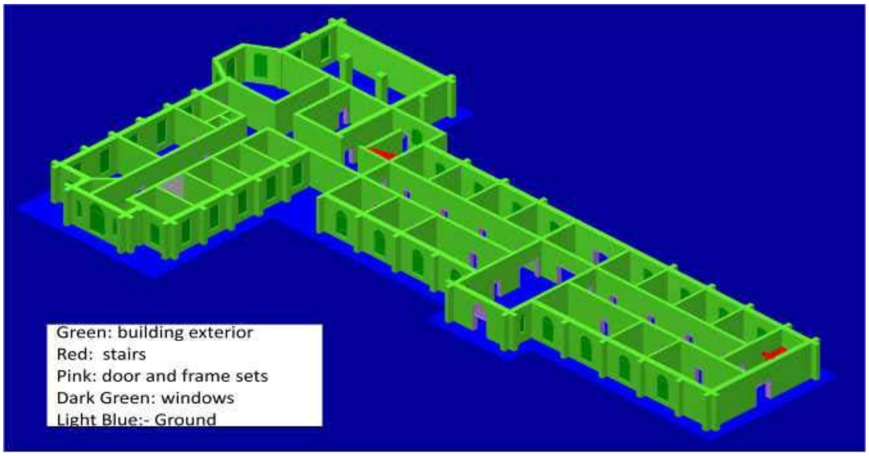

Fig. 14: (a) First floor: interior and exterior geometry.

The ceiling is composed of intersecting orthogonal arches, and is created using extrude cut operations from a solid block using wire frame arc curves obtained from the digital images (Fig. 17). Fig. 18 illustrates the arch patterns for the right side and front views, and the completed ceiling.

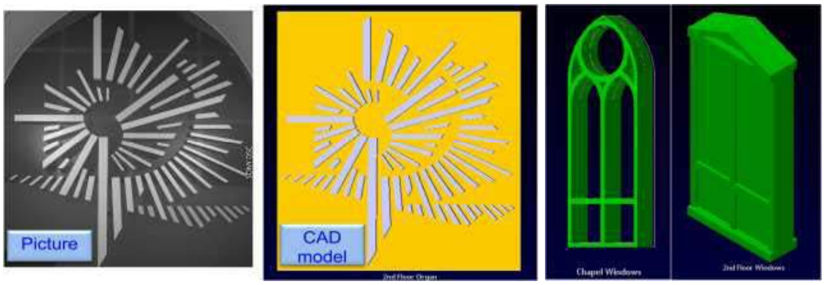

Fig. 15: (a) Actual organ, (b) CAD model of organ, (c) chapel window, and (d) second floor window.

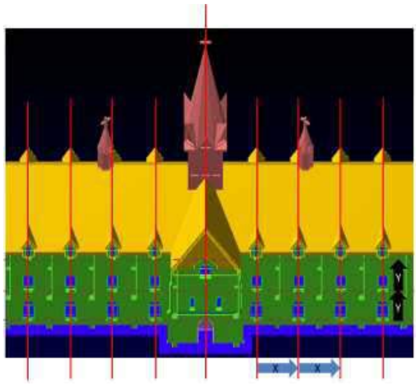

Fig. 16: Feature alignment example..

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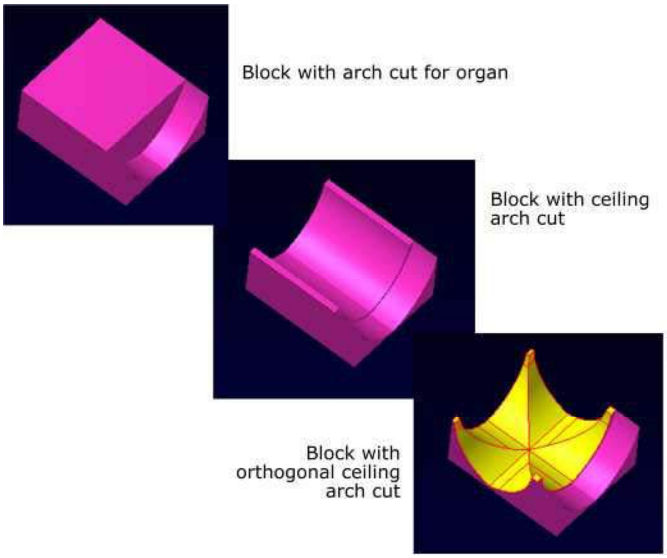

Fig. 17: Decomposed method for creating the chapel ceiling.

The roof, the roof line ornamentation and much of the steeple geometry is created from basic triangles or rectangles that have been extruded, and trimmed to reference faces (Fig. 19). There are 3 types of steeples, and they have either 4 or 8 faces. Draft angles have been utilized to obtain the steeple slope, and symmetry leveraged to create the detail on the faces, similar to the window construction. Digital images from Google Maps / Satellite were used in tandem with the collected digital images for the angle determination and the foot print of the steeples.

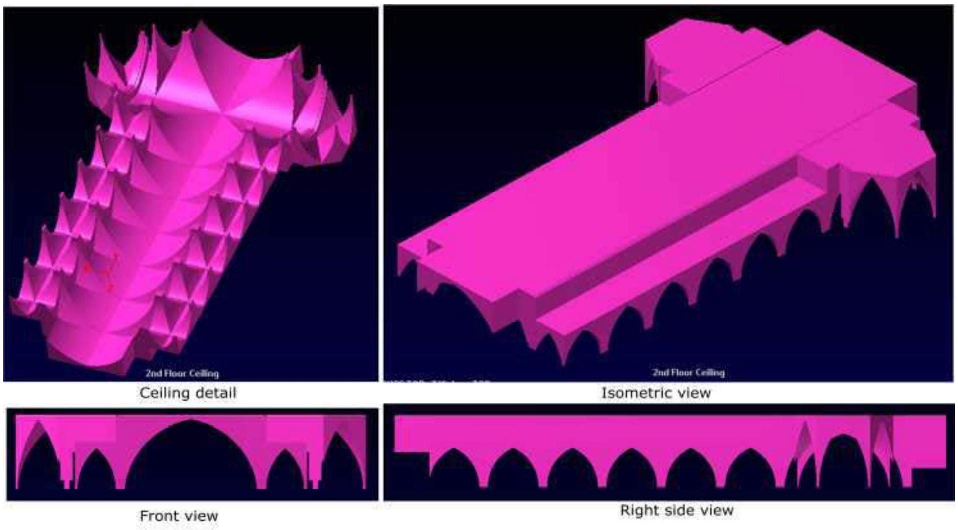

Fig. 18: Completed chapel ceiling.

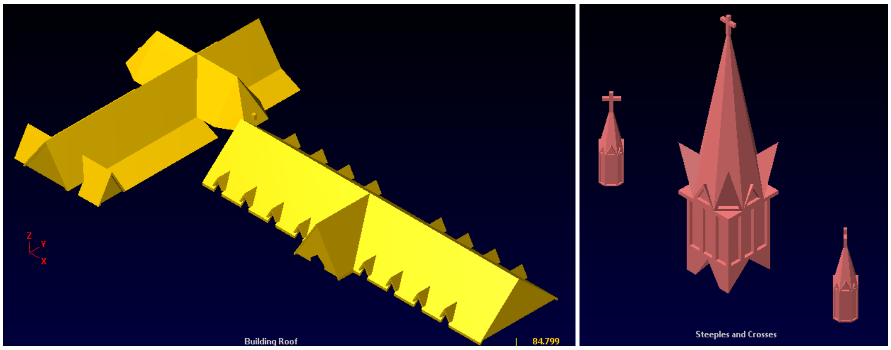

Fig. 19: (a) Roof and (b) steeples

2.6 Refine the Solid Model

Once the base model was created, it was refined to emphasize certain features as the 3DP fabrication process allows for color to be applied to any surface or tessellated facet on the model. To highlight the chapel ceiling edges with the 3DP, edge curves were created at the arch intersection to use as sweep paths, and additional solid model swept geometry was created along the edge curves. Although not as intricate the edge molding on the chapel ceiling arch intersections, the design concept is captured. Window panes and decorative features were added to several window styles (Fig. 12). Details such as staircases, the stage in the chapel, the fireplace and columns in the library were also integrated.

Additional design features were incorporated for assembly purposes as the replica was to be built using the 3DP process. Supports have been added on the side of the roof for strength, and assembly features included in order to assist with connecting the ceiling to the roof. The steeples were designed to be built separately and assembled onto the roof; hence, the faceted bases.

The final model was segmented into 13 pieces, which were then converted into an STL file format for the 3DP. Textures and colors were applied onto the surfaces. The Red Green Blue (RGB) values from the digital images were used as a reference for the brick color. The windows were tinted blue to appear to reflect skylight, and the steeples were colored green. The final CAD model and the fabricated model is illustrated in Fig. 20.

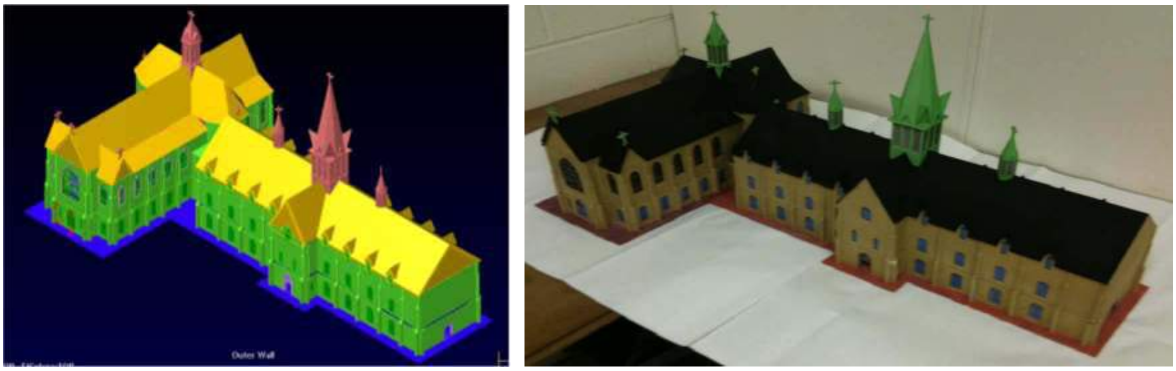

Fig. 20: Completed CAD model and completed build assembly.

2.7 Data Management

Data management is critical when reverse engineering a complex object. Although the amount of data points using these techniques is minimal compared to manipulating point cloud data, the Assumption University CAD model contains over 500 separate solids. In order to manage the data, the following rules were used:

- Wire frame geometry and solid model geometry are organized separately;
- 1^{st} floor, 2^{nd} floor, chapel, roof and steeple geometry are organized separately;
- Color coding is used to cluster feature types; and
- Reference geometry and construction geometry is never deleted but secluded.

3 SUMMARY AND CONCLUSIONS

RE techniques were applied to create a detailed solid model of Assumption University as there was no water tight model available for creating a scale model replica. The final application drove the rules for the RE process. The majority of the features is planar, contain geometric constraints with respect to symmetry and orthogonality within the features, and are positioned and oriented in repeatable patterns. The features can be constructed as solid model extrusions. Data can be collected without difficulty from digital images. Two points are required for linear segments, and ten points are used to determine arc geometry with the AF method. Geometric constraints can be readily applied to create ideal geometry as there is noise due to shadows, flaws in the building and distortion within the digital image. Images acquired at a distance are used to cross reference multiple features, provide translation vector information, and reduces image distortion. Images are calibrated to known data – either with respect to the extended tape measure or a measured feature. Similarity analysis is used to scale the data. The process is repetitive, and although minimal data is collected as compared to manipulating a point cloud, data management is essential for effective model generation and refinement. This methodology could be readily automated by employing a 'family of parts' module that leverages a constraint based modeling kernel.

To conclude, this approach is a cost effective method of recreating solid models of buildings in which the majority of features do not contain complex geometry and there is much feature repetition. Many researchers recognize the time element for establishing targets, scanning, and registration [3, 17, 21], as well as the reconstruction tasks. After the techniques were established, it took approximately 40 hours to develop the CAD model for the Dillon Hall building as shown Fig. 21 (external features only). This building is approximately 225 ft x 50 ft or 68.4 x 15.2 m and the model contains 350 solids, and includes an intricate steeple. If a detailed, accurate representation of reality were required (i.e., for archival purposes) different tools and techniques would be necessary for data collection and modeling. This methodology complements tools and techniques used to reverse engineer more elaborately styled buildings for scale model replication.

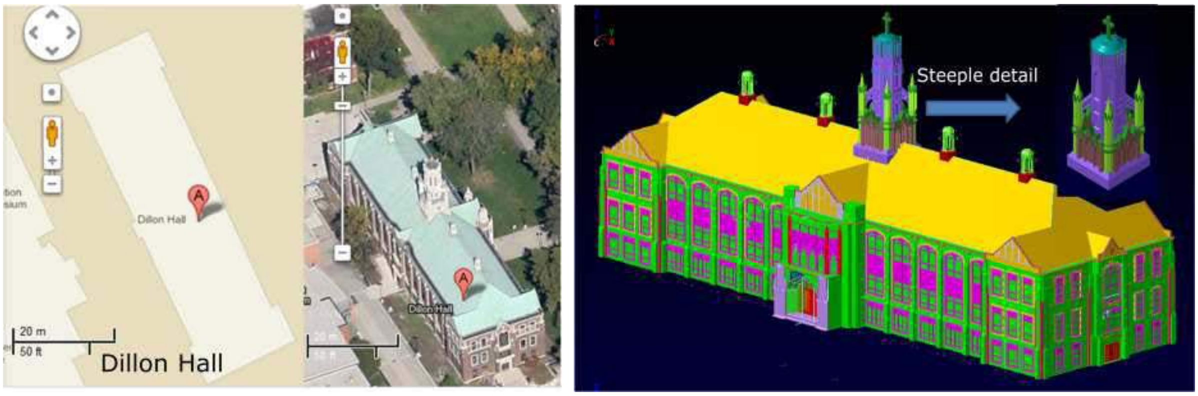

Fig. 21: (a) Completed CAD model of Dillon Hall.

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