Abstract

Objectives: The process of reconstructing a city cannot be fully automated. More human intervention is required to achieve high quality mass modeling. Our objectives are to provide a guide for the 3D graphic designers and 3D modelers in developing 3D building models. Methods: We present an up-to-date survey of the reconstruction algorithms which are further classified as point cloud based reconstruction methods and structure-aware shape reconstruction methods. We introduce various existing 3D reconstruction techniques and have compared those techniques based on shape simplification, surface completion and shape modeling methodologies. Findings: We have identified the pipeline process and technical issues encountered in each phase of the reconstruction process from a given image layout. As stated, the inverse procedural reconstruction approaches are best oriented towards the reconstruction of buildings from a given input 2D image. Also, there is a lack of systems that are capable of generating procedural rules from user interaction. Improvements: We propose a new 3D reconstruction methodology and novel framework that combines component based structure capturing and rule based modeling techniques that would best be suitable for 3D building modeling, resembling the real world buildings in future systems.

Keywords: 3D Building Modeling, 3D reconstruction, 3D Shape Analysis, Image Based Modeling, Scene Understanding

1. Introduction

Modeling and visualization of 3D objects is a great challenge in computer graphics and computer vision domains. This research activity started from the work of visionary researchers and is now becoming ubiquitous in the industry. Large scale architectural 3D building modeling is specifically receiving increasing demand in the fields of urban design, navigation, 3D games and entertainment. The modeling cost for virtual cities is high, and the cost for modeling real city is even higher. Although few entire city models were created worldwide, in a vast majority of cases the models consists of low-detailed buildings with lack of semantics. Usually, each building is represented by a coarse volume model associated with texture mapping. This certainly is appreciable for fly-over views, but it is inadequate for an immersive walk-through, while requiring at the same time significant storage and memory capacities. On the other hand, some of the city models or at least some of their landmarks are highly detailed. But this is again achieved at the price of heavy human intervention. Although the previous statement sounds as a failure for city modeling, many aspects makes it ready for reaching maturity even though some reasons are purely hardware related.

3D modeling softwares are available as well. For instance, CityEngine, Google Sketchup are some of them. But expert skills are required to model objects using these softwares. Google 3D warehouse provides any number of 3D models to be publicly available. Also, data collection has greatly advanced. Indeed, with its Street View application, Google has proved that it is possible to capture data from an entire city. Even with the availability of computationally powerful hardware and excellent softwares, the real city modeling still remains a challenge. This is mainly because of the inadequate availability of input data from
laser scans, single or multiple photographs, aerial or satellite images. Even if the data is available, the process of reconstruction of city cannot be fully automated. More human intervention is required to achieve high quality mass modeling. If semantic knowledge of the component details of the facade could be extracted from input data source, then more realistic rendering effects for buildings could be modeled by altering the component appearance effects.

In view of the above mentioned challenges, this paper aims to make a survey of relevant 3D reconstruction algorithms categorized as point cloud based reconstruction methods and structure-aware shape reconstruction methods. This survey presents a comparison and evaluation of methods considering shape simplification, surface completion and shape modeling techniques. Our objective are to provide a guide for the 3D graphic designers and 3D modelers in developing 3D building models. Also, this survey aims towards the proposal of a new 3D reconstruction methodology and novel framework that will best suit the 3D building reconstruction from a single building image layout.

2. Point Cloud based Reconstruction Methods

Surface reconstruction has become important because of its ability to acquire and process 3D point clouds. Therefore, acquiring of data and its relevant method adopted to reconstruct it are closely linked. There are various techniques of acquisition, which include active methods like LiDAR scanners, structured light scanners and optical laser-based scanners. The passive range of methods include multi-view stereo. Proliferation of these boundaries is done and it finds an optimal configuration for the boundaries through the imposition of a data fitting term in the boundary that was originally there. Very careful use of corners can help avoid the smoothing of the boundary. Extraction of surface mesh is done through advance front method. This method is used also to reconstruct architectural and CAD models, and produces a surface mesh that keeps the primitive structures that have been detected. However, this method needs adjacent boundaries to be close to each other geometrically. This may not be fulfilled in case there is a very noisy detection of primitive or in case there is presence of missing data. This is resolved by method, which extrapolates shape primitives very carefully and forms the output as extrapolated primitive’s intersection. This aforementioned

2.1 Simplification Approaches of Point Cloud Model

Point cloud model is extremely dense, and hence simplification or editing the exiting point cloud is a challenging task. We can divide the simplification approaches based on filling the missing data with geometric primitives, preserving and refining surface smoothness, symmetry based simplification methods, simplification based on structural repetitions and relationships and user interaction methods.

2.1.1 Filling with Geometric Primitives

Surface reconstruction can be enhanced by the detection of simpler geometric structures in the point cloud data. Having knowledge about a surface which can be characterized as the composition of geometric primitives is of great help with regard to filling and denoising in the missing data. This prior is not adhered to by all shapes, however, generally architectural and CAD models are characterized in this way. In order to find geometric primitives in shapes, method is a very good method. It makes the use of RANSAC to detect spheres, cones, planes, tori and cylinders through very effective ways of point sampling in order to evaluate and fit scores, both of which are based on methods that are locality sensitive. Significantly, primitives which match partially, to the point cloud are produced by this method. The shapes can be used as a collection for the purpose of reconstruction. It is important to observe that even though the method is able to locate even a small group of parameterizable shapes, it can also use pose detection for shapes that are characterized as arbitrary. It does so by merging and aligning boundaries of primitives that are adjacent to each other. Extraction of these boundaries is done and it finds an optimal configuration for the boundaries through the imposition of a data fitting term in the boundary that was originally there. Very careful use of corners can help avoid the smoothing of the boundary. Extraction of surface mesh is done through advance front method. This method is used also to reconstruct architectural and CAD models, and produces a surface mesh that keeps the primitive structures that have been detected. However, this method needs adjacent boundaries to be close to each other geometrically. This may not be fulfilled in case there is a very noisy detection of primitive or in case there is presence of missing data. This is resolved by method, which extrapolates shape primitives very carefully and forms the output as extrapolated primitive’s intersection. This aforementioned
extrapolation is formulated as a graph cut problem, where besides a generalized minimal surface area term; it also uses a data fitting term, in order to make sure there is proper alignment of the surface normal with the other intersecting primitives at the same point. It does not mean that the primitives are constrained in a local manner. Primitives having boundaries quite away can eventually intersect by this method. Method5 is able to handle missing data, it however can prove to be sensitive to primitives that are noisy, failing to give a clear model after it is extrapolated. Hence, method5 follows information of line of sight to penalize the primitives that are badly extrapolated. This aforementioned work uses the set of primitives besides an extra primitive set that are formed around the boundaries of the primitives. It makes a cell complex that reflects primitives’ extrapolation. The method6 uses point cloud, edge features and line of sight with respect to RGB images reflecting constraints to find every input shape primitive’s boundary. This produces the reconstructed surface.

In the case of indoor scene reconstruction, employing volumetric primitives to the interior space model can act as an alternative for the surface primitives. Simple cuboids are fitted in the method7 to model the volume. These cuboids are fitted to the space that is empty and is defined by the scan data’s boundaries. Construction of 2D Constructive Solid Geometry (CSG) vertical slices is done by removing and adding subject rectangles that tend to model the interior most appropriately. We can use another such method to stack up the slices in order to form a group of volumetric primitives, which produces a 3D CSG model composing the interior. This aforementioned method4 begins with the space’s volume decomposition, labelling the volumetric cells as exterior and interior via a cost function which is solved through graph cuts. The parity here is measured by intersections of rays of the vertical and horizontal extraction of the structures. These methods ensure a watertight output, and they are very robust to missing data, as just a partial volume boundary sampling is required for a nice fit.

The old traditional methodologies have one major drawback that they are not ready to be mortified easily in case if some parts of the model are inadequately elucidated. However, a hybrid approach to reconstruction was pioneered in order to solve the obstruction of methodology as presented in method6. As per this hybrid approach, in order to resample the point cloud along with implementing structural restrictions in the output, shape primitives are utilised which encompass sharp characteristics among corners and adjoining primitives at the same time when a visibility-driven prior is implemented in regions in which there was a lack of primitive fit. Nevertheless, this same approach was implemented using method10 in which the extraction of adequate fitting quality is done along with a conforming. This is further restricted by Delaunay triangulation which is built on the remaining points and polygons for the purpose of preserving the polygons in the triangulation. Robust and efficient surface reconstruction from range data is implemented in method11.

2.1.2 Preserving and Refining Surface Smoothness

Moving Least Squares (MLS)12 is one of the techniques for surface smoothness. Reconstruction is approached by these methods through the approximation of the surface as a spatially differing low-degree polynomial. To be specific, traditionally MLS formulation13 involves parameterization of points through their projection on the tangent space. After this, a bivariate polynomial of low degree is estimated by a weighted fitting in the parameterized space. The evaluating point’s projection onto the surface that is reconstructed, is then defined by the MLS as the nearest point to the bivariate polynomial. We have noted that such projection needs only an oriented normal which can also be utilized to explain a function of unsigned distance14. Resampling of the point cloud is allowed through such projections, which produces a point set surface. This surface is explained as the projection operator’s fixed point, while it is not trivial to construct a representation continuous in nature very explicitly, for example a function drawn implicitly or/and a triangle mesh which a user needs to find out the correct topology and geometry of the MLS surface. A triangle mesh is produced by advancing front methods15 which is done by laying out the triangles in order to create the fronts, determining the vertex positions via the MLS definition.

There are other forms of methods that refer to the problem of simplification with the use of the Multi-Level Partition of Unity (MPU) technique. This set of methods approaches the problem of reconstruction like a hierarchical fitting problem16. However, surfaces with errors can result from this kind of extrapolation. In order to deal with these poor fits, we can define a diffusion operator on the set of shape fits, to carry out smoothing right on the representation of the MPU17.

Reconstruction in volumetric segmentation techniques is done through a volumetric discretization
labelling, where the aim is to get the cells labelled as either exterior or interior to the surface. Method\(^\text{18}\) creates a graph Laplacian through the Delaunay triangulation. A tetrahedron is represented by every node and every edge estimates the probability of the surface being passed through the tetrahedra that is adjacent to it. The tetrahedra is segmented into exterior and interior through the Laplacian eigenvector with the minimum of non-zero eigen value. Such an approach has proven to act robustly toward outliers and noise without using normal. A watertight surface is ensured by as an explicit segmentation of volume is produced. In the regions where the data is missing, the discretization can be very coarse, resulting in a bad approximation. Method\(^\text{19}\) defines a little crust first, on the interior and exterior via a dilation operation on voxels that are pre-occupied. After imposing a graph on the crust, the local surface confidence is reflected, while the boundary nodes of the exterior and interior are connected to a source and the sink node respectively. To practice global smoothness, a little regularization constant is included by the non-terminal edges, since it has to compute a distance which is unsigned. This results in being robust to sampling which is non-uniform, misaligned and noisy. Moreover, the technique to deal with missing data is allowed by the minimal surface area regularization. Here, we observe that such kind of regularization is not present in the spectral segmentation of the approach\(^\text{18}\). However, it can be quite difficult to compute the crust in such a way that the exterior and interior can be identified.

It is more difficult to move to the piecewise smooth case from the closed case, since the ill-posed nature of this problem is applicable to every sub-feature of the suggested shape. There is a range of piecewise smooth surface features which include sharp creases, boundary components, corners, particular features like darts, cusps and tips. Moreover, the suggested surface can be a general surface having non-manifold characteristics or it can be a stratified manifold. Besides this, another problem arises from the notion that a feature is just a mere element that is present at certain scales, and we cannot decouple the feature approximation and reconstruction. An effort towards piecewise smoothness includes a category of feature-preserving techniques which are based on clearly defined representations. We can capture sharp features through anisotropic functions that are locally adapted\(^\text{20}\). An anisotropic Moving Least Squares (MLS) method is relied upon by\(^\text{21}\). The anisotropy follows the principal curvatures taken from the normal and points’ positions. Despite that, real sharp features are not produced by any technique. There are different degrees of smoothing in the features of reconstruction. Furthermore, there is just a local detection of the sharpness in the geometry. This leads to creases that are fragmented in the presence of defects\(^\text{22}\).

2.1.3 Symmetry based Simplification Methods

In the analysis of shape\(^\text{23}\), symmetry refers to a meticulously studied matter while symmetry detection refers to concentrate on finding whether local or global transformations are present on the shape that structures a part of the shape or whole shape onto itself. Finding of such transformations can be highly beneficial in reconstruction of surface from missing data and in managing noise. In the case of missing data, the methodology\(^\text{24}\) is pertinent for single-scan completion by finding small surface patches of the scan which demonstrate surface-of-revolution, bilateral, or rotational symmetry and subsequently applying the detected transformation to the remaining scan for conjecturing the missing data. However, this way an absolute model from a single view can be fabricated while not presuming the particular type of shape class. Moreover, it presumes that with the implementation of a single simple transformation, a shape can be well defined which does not always embrace. The authors are now concentrating over finding repeating elements (small subsets of point cloud) instead of enforcing global associations which can be further outlined on each other through local correspondence transformations\(^\text{25}\). The repetition of elements in a point cloud is afterwards demonstrated by them evidently in a well-patterned structure present in appropriate transformations space. However, the incomplete patches start becoming visible in this transformations space consequently the elements repeated in distinct levels of missing data can be discovered energetically while they can be also utilised for rebuilding the curtailed parts. When an affinity matrix is built, symmetries present in incomplete point clouds are found through the methodology\(^\text{26}\) while computing the symmetric points for all pairs. The major purpose of the methodology is the block-diagonal way of this matrix for several assorted kinds of symmetries like intrinsic, rotational, or bilateral. Furthermore, the authors present the way of articulating incomplete matches which further enable miscellaneous detected symmetries present in challenging point clouds which comprise of noise, missing data, and outliers. A symbol of subspace symmetries\(^\text{27}\) is utilised for easier symmetric forms in which a set of local transformations and low-dimensional shape space elucidate a symmetry group for curtailing more specific forms of shapes.
2.1.4 Structural Repetition and Relationships

With the help of symmetry transformation, it is quite obstructive to find reiterating elements present in a point cloud in several cases but if we try to find those reiterating elements directly then it can endow with more suppleness in the reconstruction procedure. In order to reconstruct building facades in noisy terrestrial LiDAR scans, this assumption is used where other materials or occlusions from vegetation can give outcomes of the missing data. Moreover, every elements' planes are perceived through in the prescribed kind of facade element while the independent elements are present at a per-plane stage. Denoising commences surrounding all elements through the individually chronicled planes after they are registered and the united facade element is schemed to be put onto each occurrence for the purpose of re-building. One of the elements has the potentiality to eradicate the noise when all the elements are utilising similar information while it can assist in filling up the missing data. The methodology has one limitation which is its constraint obligation of user interaction and it was demonstrated in the method by means of adaptively partitioning facades. The united point cloud is taken up by the strategy which further helps in proportioning it into intensive layers along with utilising a grammar elucidation which assist in dividing every intensive layer separately into facades through the finest series of grammar derivatives. A polygonal building representation may be acquired by the utilisation of facades at every intensive layer causing probable expenditure of detail in geometry because of deficiency of expression in the grammar shape. Occluded facade scans are managed by the methodology by means of carrying out an examination over vertical scan lines comprising of points’ columns beside major facade planes for identifying periodic characteristics. Every scan line requires the calculation of the Discrete Fourier Transform and afterwards utilised to extort repetitive partitioning facades. Moreover, the periodic characteristics are expanded into occluded regions so that the holes can be filled up. However, the next measure which is beneficial for finding regularity in partial scans refers to discover regularity in linked RGB imagery along with disseminating this particular information back to 3D scan for the reconstruction. This is consequently attained by method through putrefaction of the RGB image into intensive layers by means of the 3D scan and also while finding symmetries of every layer through method. It assimilates all element instances to denoise forcefully and fill in missing data present near the instances. Canonical intra-relationship refers to a simplification methodology which exists among the parts of a shape, or parts of a scene. However, these sorts of relationships can be coplanar or parallel parts, persisting orthogonality among co-axial or concentric parts, planes, and regularity in orientation. These usually exist in CAD models and urban environments because of budget considerations and fabrication constraints, and functional restrictions correspondingly. In the concerns of building reconstructions from 2.5D scans in method, the work broadened. Nevertheless, the integral point to be noted is the existence of three basic relationships in buildings i.e.,

- Roof-roof Boundary Relationships: These comprise of orthogonality and parallelism relationships.
- Roof-roof Relationships: These encompass placement and orientation equalities.
- Boundary-boundary Relationships: These relationships include position and height equality.

When these relationships are discovered by means of clustering, which is same as equality, angles etc. Then they are utilised to enlighten the primitive fitting methodology in order to fit primitives into data and relationships instantaneously. If this methodology is compared with the work, it enables vigorous reconstruction from building scans which comprises of strong structured noise.

2.1.5 Interaction Methods

However, in the procedure of surface reconstruction, the user assimilating in the process has proven to be highly favourable in tackling with challenging point clouds. The major discriminating elements those exist among the user-driven methods refer to the convenient to use as provided by an interface and the intuition level and the limit of coupling the user interaction with the underlying reconstruction procedure. User-driven methods were originated for the purpose of acquiring relevant information in the form of inputs useful for reconstruction algorithm. These tend to be encompassing and the updated techniques which strongly assimilate the core reconstruction algorithm with the user interaction. We are going to assemblage user-driven methods by the relevant sort of information importuned from the user. In order to provide useful information regarding reconstruction by the user input, the methodologies are utilised. The user input is utilised to enhance point cloud in both
methodologies along with tags categorizing various surface characteristics like sharp attributes and regions of surface smoothness. The user recognizes regions of interest by means of a simple brush tool that has the potentiality to work over the point cloud unswervingly. The sharp feature regions are quite difficult to find so tags having moving least squares are utilised to tackle them and renovate mechanically.

Moreover, the methodology\textsuperscript{40} illustrates the way of assimilating information by the user in order to direct rebuilding in an interactive fashion. The methodology of 2D-3D fusion for layer decomposition of urban facades refers to be an illustration for demonstrating user interaction needing the user to associate two-dimensional photographs and LiDAR scans by means of recognising analogous two-dimensional rectangle regions in both sorts of data sources. However, these strategies, particularly acquire topologically and watertight accurate rebuilding by means of an automatic identification of topologically feeble regions in a prescribed reconstruction. Afterwards, the user is presented these low-confidence regions for resolution through scribbles on a 2D tablet which assist in decoding to peripheral and internal restrictions, or no or probable restrictions if the user presumes that the nature of region is applicable. Subsequently, the reconstruction is revised leading to the repetition of procedure by certain more edits performed by user.

2.2 Structure Completion Approaches

Data obtained from scanning with range scanners or obtained by structure from motion from multiple images are incomplete due to occlusion or lack of correspondences. Also, the material property may have adverse effect on the scanning process. This problem becomes significant especially for when large and tall architectural buildings are scanned using lidar scanner or using large scale reconstruction techniques. There exist various techniques for surface completion that are based on such point clouds that are incomplete. The development of these methods was solely for the purpose to deal with the noise artefacts and the imperfections. Besides this, they also supported little amounts of data that would be missing. To be specific, we can divide the category of these methods into scene recovery techniques, volume recovery techniques and data-driven techniques.

2.2.1 Scene Recovery Techniques

The purpose of range scanners or laser scanners is to capture scenes that are linked in line of sight through the sensors. In order to get the reconstructed scene, every of such scan is then merged. The aforementioned approach is derived from the method\textsuperscript{41}, in which a function of signed distance is built over every range scan. Each of the scan is triangulated in detail through the structure of image lattice that it has. For a certain ray which originates at the position of the head scanner, this signed distance field is updated, on the basis of the distance between the scan and the ray’s intersection point. We can also perform space carving via the information of line of sight, through marking regions that are observed as empty by the scanner. This data is used in order to derive geometry between the regions which are unseen and the regions that are marked as empty. While this is done, it is assumed that these unseen regions are the shape’s interior. This helps solve ambiguous topology in those regions that are a part of the missing data. We can use the least possible surface area regularization to ensure smoothness of regions of the missing data, using line-of-sight as our data fitting term. The present approaches help solve such kind of formulation through models that are level-set\textsuperscript{42} as well as optimization that is graph cut\textsuperscript{43}. The tetrahedral exterior and interior labelling is done by the method\textsuperscript{44} through a Delaunay triangulation of point cloud. However, its formulation is done as a graph-cut issue by using information for line of sight. Through this method, evidence is gathered with respect to the exterior, at every tetrahedron via line of sight. Therefore, it can be assumed that there is a random distribution of outliers and hence, such a method is quite big to these types of defects. The method\textsuperscript{45} is the appropriate one to be used in order to deal with extreme kind of structured outliers and misalignment. Every range scan is merged by this approach through the use of l1 norm as the data term as well as by minimizing the gradient magnitude of the signed distance using it as the regularization term. Such kind of regularization is generally referred to as total variation denoising. It helps the algorithm to be strong to find any misalignment and to deal with structured outliers. Given that the range scan possesses a variety of scales and various densities of sampling, the method\textsuperscript{46} is used to deal with the case. In such situations, the fine-grained information can be smooth out by merging various coarse scale scans with just one fine scale scan. This allows to keep the details of fine-scale scan to be of high resolution, while general scenes can be captured too. The method\textsuperscript{47} has recently used scanner scene visibility to reconstruct thin objects like street signs. This is done by employing a point-based exhibition to reconstruct, using
a particle system to fulfil a data-fitting term, a penalizing term for the nearby points in case their normal are not in the same direction, and a source of energy to help the vector that is created by the neighbouring points that would fall on each other's tangent plane. Every point's target that is inputted and the output point is allowed only to stay at its own line of sight, helping to bound the movement of the point in the particle system. This helps simplify the optimization.

One other such kind of methods makes the use of line of sight which is not given by the scanner, but is approximated through the exterior space. Exploitation of visibility can be done even if explicit data is absent from the scanner. A non-self-occluded point cloud is determined through the visibility that is point set at every position of camera. At first, computation of the point cloud's spherical inversion takes place, which is done on the basis of the query point given. After this, identification of those points that are on the set's convex hull is made. To cater to the issue of noise levels, this method was extended by method with serious assumptions of sampling to give satisfying results. Method believes in the reconstruction of a watertight surface through carving the space that is blocked because of point cloud when seen through a set of steps that is pretty huge and random. It is expected that the input cloud will satisfy serious sampling conditions, not allowing its effectiveness through missing data and under sampling. With the aim to bring some relaxation to these policies, method came up with some solutions having inconsistencies that were detected through an observation made. This observation was that if a point's Voronoi pole appears to lie in the exterior part, it should be certain that the other Voronoi pole lies in the interior. Given that both of them are occluded or can be seen through, would reflect inconsistency. We cannot say that this method is robust as it is not possible to estimate the Voronoi poles accurately all the time, especially when the date is missing.

2.2.2 Volume Recovery Techniques

Missing data and imperfections can be found in points that are scanned through range scanners. To deal with complex kinds of missing data, we can regularize the reconstruction of surface by enforcing that the thickness of local shape differs smoothly. This thickness refers to the measurement of the local volume. As far as watertight shapes are concerned, the radii of inscribed spheres of the medial axis measure the local thickness. Since the medial axis works as an alternative for the shape's representation, it is quite hard to determine the medial axis. Method has referred to this problem on the assumption that a shape's medial axis may be approximated through curves and not surfaces, which refers to curve-skeleton. We can obtain the skeleton's reconstruction based on its organic geometry, even if missing data is present. This can be done through the exploitation of the redundant local rotational symmetry. For such kind of reconstruction, we use a process that involves three distinctive steps. Firstly, we measure the distance between the curve-skeleton and the cloud in a cylindrical way, and is parameterized. As a second step, distance in painting on the domain is performed. Lastly, this in painted point cloud is processed through any surface smoothness algorithms. A similar method for extraction of skeleton from point clouds also faced the limitation of obtaining oriented normal. It was shown through the follow up research on the method, that skeletons can be directly extracted from the point clouds that are unstructured and even if the outliers are present. We can also benefit from the volumetric smoothness by growing a deformable model that is derived from the volume itself. Method has presented this approach which gradually develops various surface fronts, under the guidance of a distance field characterized as signed. The fronts are merged and split by this method, so that the surface that lies in the growing levels can be reconstructed. Such an approach ensures an improved control and understanding of the topology that is reconstructed. It can extend to further reconstruct a curve that is skeletal, which is direct from the point cloud. In order to deal with greater number of missing data, a deformable model is presented by approach to reconstruct skeletal curves of shapes that are man-made comprising a set of tubular components like canes and metal rods. Volumetric regularization is encoded through this approach by constraining one of the solutions to the one that exhibits a differing cross-section, besides permitting geometric constraints that are of high level such as contact tangency, symmetry and planarity to make the reconstruction regularized. Tubular components that exhibit smooth radii differences piecewise are appropriate as well to model natural and organic geometry such as blood vessels or trees. There are various methods to impose volumetric smoothness on a shape's medial axis, having a better class of shapes. Method caters to reconstruction through the segmentation of point cloud turning
them into volumetric regions. In every region it takes the union of balls to achieve a surface representation which is quite coarse. This union acts as a starting surface in order to retrieve fine details. This method involves calculation of the distance measure which is defined on the point cloud that measures the probability of medial ball being created by some points. The aforementioned method acts robustly to missing data and noise, especially when nearby sheets are present. It can however fail in those areas where some surface parts that correspond to medial sheets are not present. Method\(^6\) is the most common method that involves employment of volumetric regularization. The surface which encodes the solution is evolved towards the data by level-sets. It considers surface smoothness as well as visibility, while a volumetric prior is enforced simultaneously, on the basis of the medial axis of the interface. Formation of un required holes in thin surfaces can be prevented by this technique since it will form a topological feature that would concur to the disappearing medial radii. Such holes are formed because of under-sampling. The local reflectional symmetry is encoded by the medial axis. Hence, information is allowed to be propagated very soon through the surface completely. This helps in the reconstruction of difficult data such as geometry of extremely concave areas present in a vase. Despite all the applicability described above, the applicability of this method is limited because of the unstable nature of the medial axis with respect to surface-perturbations, as well as the complex nature of its assessment.

### 2.2.3 Data Driven Techniques

Reconstructing the scenes that are composed of a certain type of complex environments and multiple types of objects is not easy at all since there is a large amount of missing data that is linked with scans, like the ones taken out of Microsoft Kinect. A better approach is using data-driven means, making use of a set of known shapes that can help in reconstructing the scene. Therefore, reconstruction of geometry involving such methods comprises of choosing the objects that are most similar in a database. If needed, it also involves deforming it to adjust the input data.

Method\(^6\) involves matching of an input point which is not complete, against a database of shapes that are complete. The most appropriate shape is deformed then, into the point cloud in order to retrieve the missing data. This helps in a watertight reconstruction, while finally in order to make the algorithm effective, it is necessary to have sound similarity between the best matching object and the input data. This problem was referred in the work\(^6\) through the use of local shape priors. A set of point cloud patches that overlap each other are compared with prior database with local shape. The surface is reconstructed using the retrieved priors. A condition that is important to be fulfilled is the dense nature of the point cloud, in order to match the cloud with the collection of complete shapes properly. When acquiring the scenes however, especially in indoor environments, the objects that are scanned can turn out to be incomplete to be able to allow this because of occlusion, the geometry can be extremely fine-grained or there might be limited directions for observations. Moreover, the objects should be segmented individually to apply these methods.

### 3. Structure Aware Shape Reconstruction Methods

Shape structure refers to the associations and arrangement between shape parts which goes ahead of low level processing and local geometry while processing and evaluating shapes at a high level. However, it concentrates more on the global intra and inter-semantic relations between the shape parts instead of focussing on their local geometry. The study of shapes’ structures has become a fundamental research topic enabling shape analysis, modelling and editing with the advent in convenient shape acquisition, simple-to-use desktop fabrication possibilities, and access to immense repositories of 3D models. In order to apprehend the structure of such shapes, a whole new structure-aware shape line processing algorithms has been come into view. The algorithms are basically of two types; rule based shape modelling and component based shape modelling having two key stages i.e., a smart processing stage and an analysis stage. The smart processing stage uses the acquired information for editing, synthesis, and exploration of novel shapes while the analysis stage refers to extracting information from input data. However, this segment of the study deals with summarization and presentation of major conceptualities and methodological strategies towards effective structure-aware shape processing. Afterwards, the key open obstructions and challenges belonging to conceptual and technical stages are listed to convenient new researchers in better exploration and contribution to this research topic.

We have classified structure aware shape reconstruction methods into two categories: Component based shape
modelling and rule based shape modelling. Component based shape modelling does not utilize rules for the shape generation whereas as the name suggests the rule based shape modelling applies rules for shape modelling.

3.1 Component based Shape Modelling

Component analysis is present in the depth of structure-aware shape processing which assists in acquiring components from a shape present in the classical segmentation problem. The correspondence problem which is present among a shape collection and not merely a pair of shapes is equally essential. In order to concentrate over both problems independently, early works on local geometric analysis are presented comprising of curvature and geodesics. Moreover, Shape Annotator Framework \(^{69}\) strived hard to assist the user to create semantic, part-based shape ontology. The data-driven approach is taken up by recent improvements, particularly in structural invariants from exemplars’ set. As\(^ {50}\) commenced, a co-analysis approach also initialized on consistent segmentation while attaining momentum on certain fronts comprising of style content separation\(^ {71}\), spectral clustering\(^ {72,73}\), co-abstraction\(^ {74}\), joint segmentation\(^ {75}\), active learning\(^ {76}\), and discovery of functional substructures\(^ {77}\). In\(^ {78,79}\) after considering more than object modelling, evaluated scene data with the utilisation of spatial contexts while applying outcomes for novel scene synthesis. Nevertheless, the methodologies of this class can be divided into structure aware editing approaches, symmetry driven shape analysis, and co-analysis of shape sets.

3.1.1 Symmetry Driven Shape Analysis

Symmetry is very influential in structure-aware processing of man-made things while symmetrical structures are anticipated to share the similar functionality. Symmetries are present in a great amount in these objects. The geometric modelling community has been utilising the methodologies of structural symmetry detection\(^ {80–82}\). The notion of upright orientation\(^ {49}\) can be utilised to comprehend functionality of man-made things which tends to be one of the early efforts in structural analysis of man-made objects. The upright orientation and symmetry demonstrate early efforts in the acquisition of high-level semantic information from geometry. To find symmetry, a number of methods have been presented\(^ {25,80,82}\). Refer to the recent surveys for images\(^ {84}\) and 3D geometry\(^ {23}\), for an in-depth discussion and detailed survey of symmetry. Like, symmetry is utilised for abstraction of incomplete shapes by means of inferring the most symmetric shape having consistency with the observation\(^ {85}\). For the purposes of modelling and shape representation, hierarchical nesting of symmetries has been investigated. Self-symmetries of the parts and inter-part symmetries are first estimated and afterwards symmetry and (part) connectivity associations are determined into a graph representation. Subsequently, a set of hand-crafted regulations replicating perceptual laws of grouping and the compactness principle determines the order of the contraction operations. The compactness principle refers to work for the simplest representation. Nonetheless, the resulting symmetric hierarchies are demonstrated to replicate object semantics and support structure-aware hierarchical shape editing. The consistency present among the hierarchical structural representations is not ascertained as acquired on a set of associated shapes.

3.1.2 Co-Analysis of Shape Sets

In last few years, people have been taking more interest in the co-analysis of sets of shapes as it helps in comprehending a shape and its components specifically and can merely be consistent by taking observations of a set of shapes having similar functionality or semantic instead of a single observation. However, it is believed that more information is generated by the analysis of a set done concurrently. But still the way of utilising the distributed set knowledge effectively is still uncertain which helps in acquiring a consistent and articulate structures’ analysis. Unsupervised co-analysis is merely reliant on the weak prior in which the input set of shapes are associated with each other demonstrating the same object class like lamps, chairs, airplanes etc. Co-segmentation refers to the core obstruction of co-analysis in which the challenge is to proportion every shape in the input set concurrently in a steadfast manner. Moreover, we acquire a labelling of the segments all over the set along with proportioning the shapes into segments. Here, the parts having similar label fulfil the same semantic objective but may be their geometries are dissimilar.

It is quite essential to acknowledge that neither unsupervised nor supervised methodology certify a perfect co-segmentation of a set because the geometry does not have the capability of expressing shape semantics entirely. Therefore, every probable geometric variation of a part cannot be captured by any descriptor specifically. The prior works of\(^ {80}\) firmly pre-aligns every shape in the set and
Afterwards, clusters the shape faces as per an underlying graph. This underlying graph associates adjacent faces present in the models and close-by faces attained after the alignment. A natural co-segmentation of the shapes has been endowed by the resulting clusters. The scale variation in the shape parts are factored out by\(^7\) through clustering the shapes first into miscellaneous styles in which a style refers to anisotropic part scales of the shapes. This way, they are capable of co-segmenting shapes presenting more variability in contrast and creating certain new shapes through transforming various styles. Nevertheless, this technique is structured to deal with merely one particular style. The co-segmentation problem same as of clustering segments attained from initial over-segmentation of the shape set is posed by\(^7\) with the utilisation of diffusion maps. But if we contrast the previous works, then the clustering is done in the area of shape descriptors instead of the spatial coordinates of the shapes. This methodology enables the handling of corresponding parts which are distinct in pose, cardinality and location then the elements challenging any strategy based on direct shape clustering or spatial alignment in geometry. Moreover, the exploitation of a key enabling characteristic of the input set which is known as third-party connections is enabled by the descriptor clustering approach. We have the possibility of developing an association between two shapes in case if they acquire essentially distinct parts and there are certain other parts present in the set which formulate an association giving an accomplished co-segmentation. The feature modelling aspect of the algorithm is advanced up in a follow-up work enhanced by\(^6\). Further, they pose and resolve a subspace clustering problem in various feature spaces rather than concatenating the diverse features into one feature descriptor. Afterwards, a joint segmentation methodology is developed by\(^5\) in which a set is utilised to help in the segmentation of individual shapes. Therefore, it does not refer to a co-segmentation methodology. Additionally, semi-supervised methodologies can be taken as unsupervised methodologies which are further helped by input coming out of the set through the user interaction. In the most updated work, it is demonstrated that the system involuntarily proposes restrictions which efficiently filter the outcomes while the user interactively attaches suitable restrictions, as per the work of\(^6\) on active learning for co-segmentation. Afterwards, the user attaches either a must-link restriction or a cannot-link restriction among recently acquisitioned segments. Afterwards, the restrictions are disseminated to the set while purifying the co-segmentation. As per their work, comparatively a very few user restrictions can direct towards perfect co-segmentation outcomes. The COSEG dataset useful for determining algorithms on co-segmentation is made accessible through their work.

### 3.1.3 Structure-Aware Editing

This section of the research study deals with a few illustration systems with an objective of editing existing shapes and the common thing in all these illustration systems is that they form their structure model on the analysis of a single input shape afterwards it is sustained as a hard or soft restriction. The structure can be preserved by free-form deformations as they comprise of non-adaptive and local way in which the local pieces’ shape is conserved autonomously of the content i.e., lacking adaptivity. In this case, no global associations are taken into account but merely a tendency present towards low-frequency bending occurs absolutely from chaining differential segments. New methods can be discovered by these two aspects. The work\(^7\) considers adaptive and local deformation while utilising a differential free-form deformation energy favouring axis-aligned stretch. After looking at differential properties like slippage analysis, curvature, it evaluates the vulnerability of local regions while reducing the model’s elasticity in vulnerable regions. Moreover,\(^8\) brings in adaptivity by amending the deformation penalties locally in order to counterpart the slippage properties of the object which further formulates a deformation behaviour which frequently mimics the mechanical systems’ behaviour i.e., joints, cylinders etc., the similar conceptuality of parts and factors is utilised in both cases. The discrepancy between both cases is the creation of constraint energy as the constraints merely respond to local differential characteristics of the deformation field in both cases whereas the behaviour is more adaptive in contrast with a standard deformation approach. The iWires\(^9\) utilises global associations. In the first method, crease lines in a triangle mesh are found which is called “wires” by the authors referring to the parts of the deformation model. Moreover, the factors refer to be the vertices of the wires and among all these parts, every prominent feature of Euclidean geometry inclusive of orthogonality, parallelity, diverse symmetries, are itemised in the analysis stage.

Afterwards, these characteristics refer to be the invariants of the deformation. Symmetric objects present under a Euclidean (rigid) transformation along with parallel lines which always remain parallel should sustain this
property. However\textsuperscript{90} came forward with such a similar idea in which the parts are object-aligned bounding boxes of shape elements that are acquisitioned through segmentation. To propagate edits to affect every symmetric element, Euclidean invariants (symmetries) are utilised. Completely constrained systems observed by\textsuperscript{91} have very limited interest in the context of interactive modelling due to their deficiency of design freedom and concentrate over under-constrained systems. Constraint functions (energies) are linearized while evaluating their null space\textsuperscript{92} as an occurrence of the Cardinality Minimization Problem which can effectively resolve the optimization utilising ideas from compressed sensing. Their proposed systems are distinct from image-based constrained reconstruction approaches as they interactively sustain manipulation with many restrictions and vertices.

### 3.2 Rule based Shape Modelling

In urban planning, computer vision and computer graphics societies, rule based shape modelling representations have been studied meticulously and were first considered as the formal design analysis, afterwards for random generation of peculiar designs and nowadays for automatic image-based reconstruction of present environments. The potentialities of these representations derived from the computer graphics viewpoint are conversed in this segment which is followed up by the production of models through a generic formal rule. The rule based shape modelling can be classified into procedural modelling and inverse procedural modelling. The procedural modelling class gains high interest in digital image synthesis whereas the inverse procedural modelling deals with computer vision.

#### 3.2.1 Procedural Modelling

Procedural modelling is taken to be generic in nature and considering the fact that it can be performed in a variety of ways, it is difficult to associate a specific single definition for the process. Instead, the process is more associated with a constructive modelling methodology, which goes to make it a challenge to assign a particular definition. Correspondingly, the methodology maybe more associated with the progression of multiple steps as per the seminal work\textsuperscript{93}. This paper would consider procedural modelling to correspond to design related to aspects of production and derivation, initially associated in a grammatical context related to shaping grammars in literature. Shape grammars have limitations in terms of automatic derivation since the latter is integrated with a sub-shape matching issues more complex than the standard sub-string equivalencies normally associated with formal grammars. The issue is further complicated since sub-shape matching is related to similarity transformations. Programming language definitions consistent to shape grammars is also considered intricate due to the complications involved with the shape definitions. The aforementioned limitations inhibit the widespread use for computerized designing or reconstruction templates and they are primarily more effective for design analysis\textsuperscript{94,95} which involve specific architectural processes being visually examined towards concluding individual grammars. The emergent concept related to grammars is particularly interesting with the conclusion of single rule grammars exhibiting complex processes and methodologies in the patterns. Of particular interest related to these grammar derivatives is the emergence of the derivatives of simple grammars which can be complex and very detailed. In the work\textsuperscript{96}, the concept contributed to the procedural modelling of urban areas. The initial input was a generalized modelling format which could be customized for large-scale environmental sites with minimal human input. Generally, these projects require huge input of data and images including the likes of topography and population density maps. Taking up from these kind of input, the model was able to draw a realistic street level layout which was utilized to demarcate construction sites. These sites were further demarcated into individual buildings which were ultimately designed in a 3D interface. This scheme was utilized in the CityEngine software using the L-systems infrastructure to design highways and road networks. There is a continuous need to consistently create geometries at run-time in urban design and keeping this in perspective, the work\textsuperscript{97} is of the opinion towards creating a pipeline towards creating pseudo-infinite cities. It is important to allow for real time data on buildings to procedurally generate buildings in terms of changing population with the variability obtained in randomness for virtual modelling platforms. To maintain the virtual environment consistently during the duration of the run, it is important that the random seed utilized to project a building at a specific location be at the same simulation which is performed through the hashing process.

In the list of works already stated, the city layout is the common objective. To allow for a 3D geometry, there is a requirement for modelling individual buildings in the layout. Minimalist visual models of buildings and urban
structures can be conveniently created with little hassles, which can be done so by extruding footprints and mapping the textures generated from the available information. Procedures involved in creating these designs will be explained upon in the course of this document. Scheme proposed in the works of Müller\cite{Müller} has enabled building modelling to be classified as a two-step process. This involves initially getting an idea of the rough volume of the building, and subsequently analysing the detailed structural elements based on the values derived. Towards designing these large scale models, a strategy of extruding the footprint goes to provide a non-flat roof model, which is very much result oriented considering that footprints can be provided for conveniently, and can be easily accessible from web based resources on the likes of OpenStreet Map. The second reason was the established fact that till the very recent past the vast majority of buildings could be conveniently represented this way. Another work in this area integrates auto-correlation based facade analysis of rectified images with shape grammars\cite{Dai}. However, the main drawback of this type of modelling approach is the level of expertise in designing rules to describe how the geometric primitives in a model is to be placed in the scene. Therefore, understanding the rules and grammars is still necessary to generate and edit models to a certain extent.

### 3.2.2 Inverse Procedural Modeling

The procedural methodologies observed thus far are generative in nature, and labelled Forward Procedural Modeling processes. Unfortunately, a major disadvantage of the rule dependent Procedural Modeling techniques is that they are more often descriptive which implies a low level of intuitiveness and control over the results derived. In the context of a city which would have multiple structures, a large amount of rules needs to be and would be therefore unmanageable for very large urban areas. Further, ordinary laymen could be challenged in utilizing such complex volumes of data. The recently introduced Inverse Procedural Modeling process could be a way to resolve the aforementioned anomalies and resolve the issues observed towards compact parameterised grammar rules and the corresponding valued associated therein which, when sequentially applied, provides a predetermined output, and is therefore considered very much applicable in the foreseeable future.

The end goal of the Inverse Procedural Modeling methodology calls for the automated provision of rules and parameters even though this is a challenge considering the presence of regions of interest in a top down context in order to hope for a specific underlying model to be in alignment and bottom up, context free. This could be since we are unaware of the actual model and simply require an estimate of the grammar from the data presented. The majority of data presented and processed require some input from the user in terms of the rules involved therein. Pairing of similar groups provides for differing transformation spaces and with the completion of the fulfilment of the spaces, they are clustered together. To conclude, the Rules Generation process involves the clusters being weighed and sorted which provides for the identification of the relevant elemental sequence. The work\cite{Gao} presented a method to extract a compact grammar from arbitrary 2D vector content. In\cite{Lee} has utilized partial symmetries to explain processes from 3D models, which in turn go to provide approaches for buildings and related structures. Considering the premise of a complex model not requiring a detailed description, in\cite{Guo} presented the Guided Procedural Modeling concept. It is important to bifurcate the space into guides, which are geometrical objects retaining specific closed limitations.

It is assumed that most construction projects have a tendency to have predominance towards three orthogonal directions, i.e., the Manhattan-World (MW) constraint,\cite{Kong} made a computerized presentation which utilized multiple images, calibrated aerially towards providing a clear geometrically synchronized representation of the buildings incorporating their textures to an extent. This methodology went towards representing buildings by utilizing a grammar which provided for buildings conforming within the MW constraints and which also added in aspects related to an initial coarse building volume. The process was possible on the basis of dual assumptions, the first being that the buildings could be represented sequentially in terms of their multiple floors, with individual floors bearing a set of connected faces and each aspect being accordingly assumed to be parallel towards a MW direction. Secondly, it was considered that individual Manhattan direction of the building floor would be differently coloured inside each image due to the lighting provided from outside sources. The course building envelope so formed is thereafter bifurcated into an array of floors, which are individually considered to be terminal symbols within the grammar. These symbols are then transformed to allow for new buildings in alignment to what had been observed aerially after considering an optimization which went through the parameter spaces.
of plausible changes, reducing the value of errors between recent and preceding constructions. In 103, presented a methodology to reconstruct entire structures with IPM utilizing template grammars, trained detectors and Structure from Motion (SfM) methodologies, all of which basically involved a grammar interpreter towards deciphering the proceeding steps to be considered. Such methods could be taken as a process to initiate the template by predetermining the actual grammar parameters, allowing for the creation of 3D simulations. To illustrate, the presentation debated upon a Doric temple. In 104, explained the challenges in constructing a façade merely from images and data ranges in the absence of structural information, and recommended a specific grammar to the data towards resolving the anomalies. This process involved a casual stroll through the façade models provided by the grammar utilizing a reversible jump Markov Chain Monte Carlo (rjMCMC) process. For the present situation, changes recommended entail the requirement of corresponding proposals, and once such is made, the acceptance of the same is dependent on a probability determined by the derivation of the input details. Another pioneering work is Bayesian learning for inverse procedural modelling 105. Inverse procedural modelling attempts to find a procedural model that generate given input and there has been a lot of research works towards encoding façade layouts. Most recently proposed work by 106 attempts to generate a meaningful split grammar that explains a given façade layout. Our research work is independently done from their work, although there is a significant similarity in both our approaches. Our work focuses more on updating a real-world building using single façade layout and building footprint. There are also significant differences in the grammar formulated by either method. The limitation of their grammar is that it works only for façade layouts that can be split by a single line. Our grammar formulation is more flexible and compactable to a variety of real-world buildings. There has been several other important research works that guide in building reconstruction after deriving a shape grammar from input façade layout. For the 3D building reconstruction, it is necessary to use the generated grammar to create sub-facades that fits into complex footprints of the building. In order to generate mass models from footprints 107 has proposed an approach for interactively modelling architectures from procedural extrusions. We are motivated from their idea and extend to real world buildings with complex real footprints with the aim of rapidly updating of a city.

4. Proposed Approach

Having discussed various approaches on digital reconstruction, one can summarize their strengths and limitations. We provide a summary of the previous literature we have discussed so far in the Table 1. Depth acquisition using range scanners to capture the 3D information of tall buildings is a difficult task. Even though sophisticated techniques are available to capture the building information as a cloud of points having individual depth measurements, still this approach ignores the constrained structure of the architecture. These methods are appropriate for improving the low-level reconstruction accuracy rather than exploring on mid-level and high-level 3D scene understanding. Despite important investment on scene representation through primitives, prior art has approached the problem from a question-able angle. The essential questions that one has to answer might be “What are the structural components of a scene?”, “How are the components organized both structurally and architecturally?”. Finding solutions for these questions are the main challenge of our work. In our approach, we propose a higher-level scene representation like structure aware shape reconstruction techniques to reconstruct the building with less information. Thus, if we can find a way to recover this information from the 2D image, the reconstruction process can be much simpler.

Summarizing the previous works, we have identified the pipeline process and technical issues encountered in each phase of the reconstruction process from a given 2D image. The Figure 1 illustrates the issues in each stage of the pipeline. The major limitation arising due to the use of a single image is incompleteness of the 3D object model because there is no information about the back sides of the object. Also, during our tests, with a wide range of different monument photographs, we observed that in some cases, the parts of the monument were only sparsely recreated. This was caused by occlusions (trees or humans) in the photograph. This limitation can be overcome by using a few more images instead of a single image. The feature extraction step also depends on the quality of the image and also we can find too many noisy features in an image. Object recognition and grouping is usually done by image segmentation. This step requires additional feature selection and multiple iterations. In the case of template matching, there may be too many templates and the question here is how to match the templates. 3D depth estimation from the 3D position of the depth
### Table 1. Comparison of digital reconstruction approaches

| Simplification approaches of point cloud model | Surface completion approaches | Component based shape modeling | Rule-based shape modeling |
|----------------------------------------------|-------------------------------|-------------------------------|---------------------------|
| **Digital 3D Reconstruction**                | **Scene recovery techniques** | **Symmetry driven shape analysis** | **Procedural modeling** |
| **Filling with geometric primitives**        | 1. Robust to missing data 2. Ensures a watertight output | 1. Deal with noise artifacts & imperfections 1. Cannot deal with complex kinds missing data | 1. Utilized in the creation of complicated high-level structures 2. Easy for part connectivity and relationships | 1. Fast prototyping 2. Mass modeling 3. Easy creation of variations of original model |
| **Preserving and refining surface smoothness** | 1. Features like sharp creases, boundary components, corners are preserved | 1. Real sharp features are not produced 2. Different degrees of smoothing in the features 3. Formation of creases that are fragmented in the presence of defects | 1. Express the shape semantics in hierarchical approach | 1. Fast prototyping 2. Mass modeling 3. Easy creation of variations of original model |
| **Symmetry based simplification methods**    | Reconstruction of surface from missing data 2. Cannot find repetitive elements in the point cloud | **Data driven techniques** | 1. Utilizing the distributed set knowledge effectively is still uncertain 2. Active learning for co-segmentation is required | 1. Efficiency depends on the input image or exemplar 3D model. |
| **Structural repetition and relationships**   | 1. Assist occlusion recovery 2. Assist in filling up of missing data | 1. Higher user intervention 2. Not useful for less repetitive structures | 1. Limited editing facility 2. Lacks design freedom | 1. Not intuitive 2. Requires manual production of rules |
| **Interaction methods**                      | 1. Convenient user interface and intuition level 2. Coarse results can be refined by user with few edits | 1. Higher user intervention | | |
measurements of the feature vector is another challenging task. 3D position estimation and camera calibration is also a major challenge for 3D reconstruction. The identified issues are rather challenging and they make 3D reconstruction an ill-posed problem. Also, while viewing a 3D pose from a 2D image, we can find more than one 3D possibilities, this increases the space for finding an optimal solution. We can think of a 3D scene as composed of 3D objects that are illuminated by light sources and that project as components in a 2D image. Boundaries between 3D objects or changes in illumination of these 3D objects results in contrast edges or contours in the 2D image forming components that compose an object in the scene. Here, the real world object is the building in the scene. Identifying the components of the building and reconstructing them to 3D and integrating them in their exact spatial and structural locations will help to regenerate the building with ease. From the comparison study in Table 1, we conclude that the best method suitable for our goal is structure aware shape reconstruction.

To tackle our problem, we introduce a novel framework to generate real-world 3D buildings from a single facade layout that adapt to the real footprint data automatically. Building facade layout encodes expected architectural constraints and is able to derive complex instances using shape grammars. Facade components are extracted from the facade layout and organized as a repetitive shape tree. A meaningful grammar representation is automatically extracted from the hierarchical facade subdivision. We extend the previous approaches of procedural building models to a constraint-based framework for the recovery of the hidden parts of the building. We then provide an interactive editing, enabling facade syntax preserving manipulations for updating of the structural topology given a different view of the building. The semi-automatic and interactive reconstruction methodology is illustrated shown in Figure 2.

5. Conclusion and Future Works

Several 3D reconstruction algorithms and methodologies studied in this paper. Summarizing the previous works, we have identified the pipeline process and technical issues encountered in each phase of the reconstruction process from a given image layout. As stated, the inverse procedural reconstruction approaches are best oriented towards the reconstruction of buildings from a given input 2D image. Also, there is a lack of systems that are capable of generating procedural rules from user interaction.

From the research and study of these algorithms, we have formulated our research problem to rapidly reconstruct a 3D building model that exactly matches the building photograph using limited prior information. We have proposed a novel framework combining the benefits of both component based structure capturing and rule based modeling techniques. In order to state the feasibility of the method, we can implement and discuss its limitations as future work.

6. References

1. Schnabel R, Wahl R, Klein R. Efficient ransac for point-cloud shape detection. Computer Graphics Forum. 2007; 26(2):214–26.
2. Drost B, Ulrich M, Navab N, Ilic S. Model globally, match locally: Efficient and robust 3D object recognition. IEEE CVPR. 2010. p. 198–1005.
3. Scheidegger CE, Fleishman S, Silva CT. Triangulating point set surfaces with bounded error. Proc of the EG/SIGGRAPH Symposium on Geometry processing; Switzerland. 2005. p. 63–72.
4. Schnabel R, Degener P, Klein R. Completion and reconstruction with primitive shapes. Computer Graphics Forum (Proc of Eurographics). 2009; 28(2):503–12.
5. Chauve AL, Labatut P, Pons JP. Robust piecewise-planar 3D reconstruction and completion from largescale unstructured point data. IEEE CVPR; 2010. p. 1261–8.
6. Reisner-Kollmann I, Maierhofer S, Purgathofer W. Reconstructing shape boundaries with multimodal constraints. Computers and Graphics. 2013; 3(37):137–47.
7. Xiao J, Furukawa Y. Reconstructing the worlds museums. ECCV; 2012. p. 668–81.
8. Oesau S, Lafarge F, Alliez P. Indoor scene reconstruction using primitive-driven space partitioning and graphcut. Proc of EG workshop on Urban Data Modeling and Visualisation; Girona, Spain. 2013. p. 9–12.
9. Lafarge F, Alliez P. Surface reconstruction through point set structuring. Computer Graphics Forum (Proc of Eurographics). 2013; 32(2):225–34.
10. Van Kreveld M, Van Lankveld T, Veltkamp RC. Watertight scenes from urban lidar and planar surfaces. Computer Graphics Forum. 2013; 32(5):217–28.
11. Labatut P, Pons JP, Keriven R. Robust and efficient surface reconstruction from range data. Computer Graphics Forum. 2009; 28(8):2275–90.
12. Cheng ZQ, Wang YZ, Li B, Xu K, Dang G, Jin SY. A survey of methods for moving least squares surfaces. Proceedings of the 5th Eurographics/IEEE VGTC Conference on Point-Based Graphics; Switzerland. 2008. p. 9–23.
13. Alexa M, Behr J, Cohen-Or D, Fleishman S, Levin D, Silva C. Computing and rendering point set surfaces. Trans on Visualization and Computer Graphics. 2003; 9(1):3–15.
14. Amenta N, Kil YJ. Defining point-set surfaces. ACM Trans on Graphics. 2004; 23(2):264–70.
15. Schreiner J, Scheidegger CE, Fleishman S, Silva CT. Direct (re)meshing for efficient surface processing. Computer Graphics Forum. 2006; 25(3):527–36.
16. Ohtake Y, Belyaev A, Alexa M, Turk G, Seidel H. Multi-level partition of unity implicits. ACM Trans Graph. 2003; 22(2):463–70.
17. Nagai Y, Ohtake Y, Suzuki H. Smoothing of partition of unity implicit surfaces for noise robust surface reconstruction. Computer Graphics Forum (Proc of the Symposium on Geometry Processing). 2009; 28(5):1339–48.
18. Kolluri R, Shewchuk JR, O’Brien JE. Spectral surface reconstruction from noisy point clouds. Proc of the EG/SIGGRAPH Symposium on Geometry Processing; 2004. p. 11–21.
19. Hornung A, Kobbelt L. Robust reconstruction of watertight 3D models from non-uniformly sampled point clouds without normal information. Computer Graphics Forum (Proc of the Symposium on Geometry Processing); 2006. p. 41–50.
20. Dinh HQ, Turk G, Slabaugh G. Reconstructing surfaces using anisotropic basis functions. International Journal of Computer Vision. 2001; 606–13.
21. Adamson A, Alexa M. Anisotropic point set surfaces. Proc AFRIGRAPH; 2006. p. 7–13.
22. Avron H, Sharf A, Greif C, Cohen-Or D. 1-sparse reconstruction of sharp point set surfaces. ACM Trans on Graphics. 2010; 29(5):1–12.
23. Mitra NJ, Pauly M, Wand M, Geylan D. Symmetry in 3D geometry: Extraction and applications. Computer Graphics Forum (STAR Proceedings of Eurographics). 2013; 32(6):1–23.
24. Law AJ, Aliaga DG. Single viewpoint model completion of symmetric objects for digital inspection. Computer Vision and Image Understanding. 2011; 115(5):603–10.
25. Pauly M, Mitra NJ, Wallner J, Pottmann H, Guibas LJ. Discovering structural regularity in 3D geometry. ACM Trans Graph. 2008; 27(3):1–11.
26. Lipman Y, Chen X, Daubechies I, Funkhouser T. Symmetry factored embedding and distance. ACM Trans on Graphics. 2010; 29(4):1–12.
27. Berner A, Wand M, Mitra NJ, Mewes D, Seidel HP. Shape analysis with subspace symmetries. Computer Graphics Forum. 2011; 30(2):277–86.
28. Zheng Q, Sharf A, Gan Y, Li Y, Mitra NJ, Cohen-Or D, Chen B. Non-local scan consolidation for 3D urban scenes. ACM Trans Graph. 2010; 29(4):1–9.
29. Shen CH, Huang SS, Fu H, Hu SM. Adaptive partitioning of urban facades. Proc of ACM SIGGRAPH Asia. 2011; 30(6):184.
30. Wan G, Sharf A. Grammar-based 3D facade segmentation and reconstruction. Computers and Graphics. 2012; 36(4):216–23.
31. Friedman S, Stamos I. Online facade reconstruction from dominant frequencies in structured point clouds. IEEE CVPR; 2012. p. 1–8.
32. Li Y, Zheng Q, Sharf A, Cohen-Or D, Chen B, Mitra NJ. 2D-3D fusion for layer decomposition of urban facades. ICCV; 2011. p. 882–9.
33. Wu C, Frahm JM, Pollefeys M. Detecting large repetitive structures with salient boundaries. ECCV; 2010. p. 142–55.
34. Zhou QY, Neumann U. 2.5D building modeling by discovering global regularities. CVPR; 2012. p. 326–33.
35. Li Y, Wu X, Chrysathou Y, Sharf A, Cohenor D, Mitra NJ. Globfit: Consistently fitting primitives by discovering global relations. ACM Trans Graph. 2011; 30(4):52.
36. Sadidi J, Talebzadeh M, Rezaian H, Firouzabadi PZ. Designing 3D semantic model in LOD4 to simulate building utility network. Indian Journal of Science and Technology. 2015 Jul; 8(16):1–9.
37. Sivaranjani P, Kumar AS. 3D VLSI non-slicing floor planning using modified corner list representation. Indian Journal of Science and Technology. 2015 Dec; 8(35):1–6.
38. Guennebaud G, Gross M. Algebraic point set surfaces. ACM Trans Graph. 2007; 26(3):23.
39. Fleishman S, Cohen-Or D, Silva CT. Robust moving least-squares fitting with sharp features. ACM Trans Graph. 2005; 24(3):544–52.
40. Sharf A, Lewiner T, Shklarski G, Toledo S, Cohen-Or D. Interactive topology-aware surface reconstruction. ACM Trans Graph. 2007;26(3):43.
41. Curless B, Levoy M. A volumetric method for building complex models from range images. Proc of ACM SIGGRAPH; 1996. p. 303–12.
42. Whitaker R. A level-set approach to 3D reconstruction from range data. International Journal of Computer Vision. 1998; 29(3):203–31.
43. Lempitsky V, Boykov Y. Global optimization for shape fitting. IEEE CVPR; 2007. p. 1–8.
44. Labatut P, Pons J P, Keriven R. Robust and efficient surface reconstruction from range data. Computer Graphics Forum. 2009; 28(8):2275–90.
45. Zach C, Pock T, Bischof H. A globally optimal algorithm for robust tv-l1 range image integration. ICCV; 2007. p. 1–8.
46. Fuhrmann S, Goesele M. Fusion of depth maps with multiple scales. Proc of ACM SIGGRAPH Asia; 2011. p. 148.
47. Ummenhofer B, Brox T. Point-based 3d reconstruction of thin objects. ICCV; 2013. p. 969–76.
48. Katz S, Tal A, Basri R. Direct visibility of point sets. ACM Trans Graph. 2007; 26(3):24.
49.Gallery R, Tripathi P, Sheffer A, Mitra NJ. Visibility of noisy point cloud data. Computers and Graphics. 2010; 34(3):219–30.
50. Chen YL, Chen BY, Lai SH, Nishita T. Binary orientation trees for volume and surface reconstruction from unoriented point clouds. Computer Graphics Forum. 2010; 29(7):2011–9.
51. Chen YL, Lee TY, Chen BY, Lai SH. Bipartite polar classification for surface reconstruction. Computer Graphics Forum. 2011; 30(7):2003–10.
52. Amenta N, Bern M. Surface reconstruction by voronoi filtering. Discrete and Computational Geometry. 1999; 22(4):481–504.
53. Tagliasacchi A, Zhang H, Cohen-Or D. Curve skeleton extraction from incomplete point cloud. ACM Trans Graph. 2009; 28(3).
54. Seung-Woon J, Cheong-Hwan L, Young-Cheol J. A study on the work environment and VDT syndrome in radiation technologists working in the area of 3D processing. Indian Journal of Science and Technology. 2015 Aug; 8(18):1–7.
55. Cao J, Tagliasacchi A, Olson M, Zhang H, Su Z. Point cloud skeletons via laplacian based contraction. Proc of IEEE Shape Modeling International; 2010. p. 187–97.
56. Huang H, Wu S, Cohen-Or D, Gong M, Zhang H, Li G, Chen B. 1l-medial skeleton of point cloud. CM Trans Graph. 2013; 32(4):65–70.
57. Sharf A, Lewiner T, Shamir A, Kobelt L, Cohen-Or D. Competing fronts for coarse-to-fine surface reconstruction. Computer Graphics Forum. 2006; 25(3):389–98.
58. Sharf A, Lewiner T, Shamir A, Kobelt L, Cohen-Or D. On-the-fly curve-skeleton computation for 3D shapes. In Computer Graphics Forum. 2007; 26(3):323–8.
59. Li G, Liu L, Zheng H, Mitra NJ. Analysis reconstruction and manipulation using arterial snakes. ACM Trans Graph; 2010; 29(6).
60. Neubert B, Franken T, Deussen O. Approximate image-based tree-modeling using particle flows. ACM Trans Graph. 2007; 26(3):88–75.
61. Runions A, Fuhrer M, Lane B, Federl P, Rolland-Lagan AG, Rusinkiewicz P. Modeling and visualization of leaf venation patterns. ACM Trans Graph. 2005; 24(3):702–11.
62. Livny Y, Yan F, Olson M, Chen B, Zhang H, El-Sana J. Automatic reconstruction of tree skeletal structures from point clouds. ACM Trans Graph. 2010; 29(6).
63. Berger M, Silva CT. Medial kernels. Computer Graphics Forum (Proc of Eurographics). 2012; 31(2):795–804.
64. Tagliasacchi A, Olson M, Zhang H, Hamarneh G, Cohen-Or D. Vase: Volume-aware surface evolution for surface reconstruction from incomplete point clouds. Computer Graphics Forum. 2011; 30(5):1563–71.
65. Pauly M, Mitra NJ, Giesen J, Gross MH, Guibas LJ. Example-based 3D scan completion. Proc of the EG/SIGGRAPH Symposium on Geometry processing; 2005. p. 23–32.
66. Gal R, Shamir A, Hassner T, Pauly M, Cohen-Or D. Surface reconstruction using local shape priors. Computer Graphics Forum. 2007; 253–62.
67. Shamir A. A survey on mesh segmentation techniques. Computer Graphics Forum. 2008; 27(6):1539–56.
68. Van Kaick O, Zhang H, Hamarneh G, Cohen-Or D. A survey on shape correspondence. Computer Graphics Forum. 2011; 30(6):1681–707.
69. Attene M, Robbiano F, Spagnuolo M, Falcidieno B. Characterization of 3D shape parts for semantic annotation. Computer Aided Design. 2009; 41(10):756–63.
70. Golovinskiy A, Funkhouser T. Consistent segmentation of 3D models. Computers and Graphics (Proc of SMI). 2009; 33(3):262–9.
71. Xu K, Li H, Zhang H, Cohen-Or D, Xiong Y, Cheng Z. Style-content separation by anisotropic part scales. ACM Transactions on Graphics. 2010; 29(6).
72. Sidi O, Van Kaick O, Kleinman Y, Zhang H, Cohen-Or D. Unsupervised co-segmentation of a set of shapes via descriptor-space spectral clustering. ACM Trans on Graphics. 2011; 30(6).
73. Kim Vg, Mitra N, Diverdi S, Funkhouser T. Exploring collections of 3D models using fuzzy correspondences. Trans on Graphics. 2012; 31(4):1–11.
74. Udayan J. Divya. Co-abstraction of shape collections. ACM Transactions on Graphics. 2013; 31(6):1–11.
75. Huang Q, Koltun V, Guibas L. Joint shape segmentation with linear programming. ACM Trans Graph. 2011; 30(6):1–12.
76. Wang Y, Asafi S, Van Kaick O, Zhang H, Cohen-Or D, Chen B. Active co-analysis of a set of shapes. ACM Transactions on Graphics. 2012; 31(6).
77. Zheng Y, Cohener D, Mitra NJ. Functional substructures for part compatibility. Computer Graphics Forum. 2013; 32(2):195–204.
78. Fisher M, Savva M, Hanrahan P. Characterizing structural relationships in scenes using graph kernels. ACM Trans Graph. 2011; 30(4):1–12.
79. Fisher M, Ritchie D, Savva M, Funkhouser T, Hanrahan P. Example-based synthesis of 3D object arrangements. ACM Transactions on Graphics. 2012; 31(6):1–11.
80. Simari P, Kalogerakis E, Singh K. Folding meshes: Hierarchical mesh segmentation based on planar symmetry. Proc Symp Geometry Processing; 2006. p. 111–9.
81. Mitra NJ, Guibas LJ, Pauly M. Partial and approximate symmetry detection for 3D geometry. ACM Trans Graph. 2006; 25(3):560–8.
82. Podolak J, Shilane P, Golovinskiy A, Rusinkiewicz S, Funkhouser T. A planar-reflective symmetry transform for 3D shapes. ACM Trans Graph. 2006; 25(3):549–59.
83. Fu H, Cohen-Or D, Dror G, Sheffer A. Upright orientation of man-made objects. ACM Trans Graph. 2008; 27(3):1–7.
84. Liu Y, Hel-Or H, Kaplan CS, Gool LV. Computational symmetry in computer vision and computer graphics. Foundations and Trends in Computer Graphics and Vision. 2010; 5(1):1-195.
85. Thrun S, Wegbreit B. Shape from symmetry. Proc Int Conf Computer Vision; 2005. p. 1824–31.
86. Hu R, Fan L, Liu L. Co-segmentation of 3D shapes via subspace clustering. Computer Graphics Forum. 2012; 31(5):1703–13.
87. Kraevoy V, Sheffer A, Shamir A, Cohenor D. Non-homogeneous resizing of complex models. ACM Trans Graph. 2008; 27(5):1–9.
88. Xu W, Wang J, Yin K, Zhou K, Van De Panne M, Chen F, Guo B. Joint-aware manipulation of deformable models. ACM Trans Graph. 2009; 28(3):1–10.
89. Gal R, Sorkine O, Mitra N, Cohen-Or D. iWires: An Analyze-And-Edit Approach To Shape Manipulation. ACM Trans Graph. 2009; 28(3):1–10.
90. Zheng Y, Fu H, Cohen-Or D, Au OKC, Tai CL. Component-wisecontrollersforstructure-preservingshapemanipulation. Computer Graphics Forum. 2011; 30(2):563–72.
91. Habbecke M, Kobelt L. Linear analysis of nonlinear constraints for interactive geometric modeling. Computer Graphics Forum. 2012; 31(2):641–50.
92. Bokeloh M, Wand M, Seidel H P, Kolten V. An algebraic model for parameterized shape editing. ACM Transactions on Graphics. 2012; 31(4):1–10.
93. Newell M. The utilization of procedure models in digital image synthesis [PhD thesis]. The University of Utah; 1975.
94. Stiny G, Mitchell WJ. The Palladian grammar. Environment and Planning B. 1978; 5(1):5–18.
95. Flemming U. More than the sum of parts: the grammar of Queen Anne houses. Environment and Planning B Planning and Design. 1987; 14(3):323–50.
96. Muller P, Parish YIH. Procedural modeling of cities. SIGGRAPH; 2001. p. 301–8.
97. Greuter S, Parker J, Stewart N, Leach G. Real-time procedural generation of ‘pseudo infinite’ cities. International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia; 2003. p. 87–95.
98. Muller P, Vereenooghe T, Wonka P, Van Gool L. Procedural 3D reconstruction of puuc buildings in xkipché. International Symposium on Virtual Reality, Archeology and Cultural Heritage; 2006. p. 139–46.
99. Teboul O, Kokkinos I, Simon L, Sourakis PK, Paragios N. Shape grammar parsing via reinforcement learning. 2011. p. 2273–80.
100. Stava O, Benes B, Mech R, Aliaga DG, Kristof P. Inverse procedural modeling by automatic generation of L-systems. Computer Graphics Forum. 2010; 29(2):665–74.
101. Benes B, Stava O, Mech R, Miller G. Guided procedural modeling. Computer Graphics Forum. 2011; 30(2):325–34.
102. Vanegas C A, Aliaga D G, Benes B. Building reconstruction using manhattan-world grammars. IEEE CVPR; 2010. p. 358–65.
103. Mathias M, Martinovic A, Weissenberg J, Van Gool L. Procedural 3D building reconstruction using shape grammars and detectors. International Conference on 3D Imaging, Modeling, Processing, Visualisation and Transmission; 2011. p. 304–11.
104. Ripperda N, Brenner C. Application of a formal grammar to facade reconstruction in semiautomatic and automatic environments. Proc AGILE Conference on GIScience; 2009. p. 1–12.
105. Martinovic A, Van Gool L. Bayesian grammar learning for inverse procedural modeling. IEEE CVPR; 2013. p. 201–8.
106. Wu F, Yan D M, Dong W, Zhang X, Wonka P. Inverse procedural modeling of facade layouts. ACM TOG 34. 2014. p. 1–10.
107. Kelly T, Wonka P. Interactive architectural modeling with procedural extrusions. ACM Trans on Graph. 2011; 30(2):14–24.