A SEQUENTIAL APPROACH TO CAPTURE FINE GEOMETRIC DETAILS FROM IMAGES

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ABSTRACT:

We present a sequential multi-stage segment-based modelling from images procedure designed to model the fine geometric details with high-resolution meshes. Results from one stage guide the next stage. The objective is to increase the geometric details at the modelling phase in an automatic and reliable manner to achieve photo-realistic visualisation for a variety of applications. In the first stage of this approach, basic shapes are determined with an interactive approach while in the subsequent stages fine details are added automatically, on a segment by segment basis, using dense stereo matching and shape from shading. The two techniques are used in a complementary manner and selecting which one to use is based on preset logical rules. Since we only need to compute the difference between the detailed model and the basic model produced in the first stage, the approach works in a more robust and reliable manner as compared to computing absolute coordinates. The approach has been extensively tested on hundreds of actual data and the results proved that it is effective, stable, and can model many types of surface details.

1. INTRODUCTION

Richly detailed models of real world objects are essential for many interactive visualization applications. The resolution of the rendered model should ideally match what is perceptible by the human eyes on a real visit. There are many ways to create a virtual representation, as panoramas or image-based rendering, but a textured 3D geometric model is the most desirable since it allows unrestricted interactive visualisation and manipulation. This offers the user the freedom to choose any viewpoint at a variety of lighting conditions. It is therefore important that the model has dense 3D data (high resolution meshes) on all surfaces to guarantee a realistic experience even at close up. Several sensing technologies are available. Laser scanners can capture relatively accurate and complete details, but at least for now they are costly, usually bulky, not east to use, influenced by surface properties, and impractical on large or distant objects. Also, as a laser scanner is intended for a specific range and volume, one designed for close range is not suitable for medium or long range. Image-based modelling (IBM) techniques although can produce accurate and realistic-looking models remain highly interactive since current fully automated methods are still unproven in real applications. The needed interactivity will inevitably limit the amount of details a model can have. Even when rich texture maps are used, the models without the fine geometric details and surface irregularities will exhibit very smooth, flat-looking, surfaces and polygonised silhouettes that are easily detected by the human eye. Since IBM has the advantage of low cost sensors and the flexibility and the ease with which the data can be captured, it is thus very desirable if it can also create very detailed high-resolution models. There are some alternatives for capturing the fine details from images, primarily:

1. Dense stereo matching.
2. Shape from shading (SFS), shadows, or textures.
3. Mapping techniques: Although most do not add to the geometry, they do increase realism; *view dependent texture mapping* which projects different image depending on user view point, *bump mapping* which modifies pixel surface normal before lighting computation, and *displacement mapping* which modifies pixel screen coordinates.

Occlusions, lack of texture, and light variations between images are persistent problems for stereo matching especially with widely separated views. In our approach, the problems are reduced by: using the basic geometric model to narrow the search; and setting up logical rules for selecting image regions where the matching can be reliably applied. In areas where stereo matching is ineffective, shape changes may be resolved from intensity or shade variations. The changes in intensity across the surface due to surface reflection properties and position and orientation (angle of the surface normal) relative to the light source and the camera is a direct function of surface shape - the larger the angle the darker the surface. However, SFS techniques usually do not recover accurate shapes since they are based on approximate assumptions to resolve its under-determined formulation. We implement SFS to bring out small variations on surfaces and details that are function of shading on un-textured surfaces such as bricks, stones, and carvings. In our approach, both stereo matching and SFS are used to compute the deviation from the basic model not the absolute coordinates. The approach has several hierarchical steps:

1. Create a basic model of the object segmented-surfaces.
2. Apply stereo matching constrained by the basic model and camera parameters on suitably textured parts.
3. Apply SFS on the remaining parts.
4. For areas still unresolved, revert back to the basic model.

This approach has the following advantages:

1. Uses a small number of photos.
2. Interactivity is limited to measuring of seed points and dividing the scene into segments. Usually no post editing of the model is required.
3. Fine details are created automatically using either stereo matching or SFS, depending on which is best suited.

4. The details are computed as the *deviation* from basic shapes rather than absolute coordinates, which makes the stereo matching and SFS more reliable.
5. Takes advantage of symmetry and repeated segments by copying and pasting already modelled parts.

Although modelling of the Bi-directional Reflectance Distribution Function (BRDF) and inverse global illumination are essential to render the model under varying lighting conditions, which is significant for photo-realism, they are beyond the scoop of this paper and we will focus only on the geometric details. The rest of the paper is organised as follows. The next section discusses relevant previous work, and then the proposed approach is detailed in section 3. Several experimental test results are shown in section 4 followed by conclusions.

2. PREVIOUS WORK

Many techniques to increase the level of details in image-based models are available. In the following sub-sections we discuss the most applicable to our work, mainly methods for creating basic shapes and those capable of capturing fine geometric details, mainly stereo matching, SFS including those combined with stereo matching, and runtime mapping techniques for adding the details at the end of the rendering phase.

2.1 Image-based modelling of basic shapes

The Façade system [Debevec et al., 1996] has been developed to create 3D models of architectures from small number of photographs. The basic geometric shape of a structure is first recovered interactively using models of polyhedral elements. In this step, the actual size of the elements and camera pose are computed assuming that camera intrinsic parameters are known. The second step automatically adds geometric details by stereo matching, constrained by the model constructed in the first step. Since the assumed shapes determine camera poses and all 3D points, the results are as accurate as the structure elements match those shapes. Gruen et al, 2004, also used stereo matching to add details to an interactively measured seed points on the basic model. El-Hakim, 2002, designed a semi-automatic approach to model regular shapes such as blocks, arches, columns, and windows using a small number of interactively measured seed points. Camera positions and the 3D coordinates of seed points are determined with bundle adjustment, and then the remaining points completing those shapes are automatically added. Lee and Nevatia, 2003, developed another semi-automatic technique to model architectures. The models are created in hierarchical manner by dividing the structure into basic shape, façade textures, and more detailed geometry such as columns and windows. The procedure requires the user to interactively provide shape information such as width, height, radius, and spacing then the shape is completed automatically. Full automation of IBM techniques is a very active area of research in computer vision. Such techniques rely on constraints from a priori assumption about surface shapes and relationships between surfaces [Grossmann and Santos-Victor, 2005, Dick et al., 2004, Werner and Zisserman, 2002]. Without any knowledge about the object, the modelling procedure may still be automated using constraints derived recursively from the data such as visibility constraints [Hilton, 2005]. However, full automation with no user intervention whatsoever remains experimental and to our knowledge no large complex site model was completed based purely on fully automated methods. Only selected sections of some structures have been automatically modelled [Pollefeys et al., 2004]. Some software tools for IBM are commercially available, but they are not very flexible or automated thus they can usually be used for only simple shapes.

2.2 Stereo matching

Brown et al, 2003 and Scharstein and Szeliski, 2002, give good overviews and analysis of the recent advances in stereo matching techniques. Feature-based methods work best with scale-invariant features extracted with specially designed image operators [Lowe, 2004]. Area-based methods [e.g. Gruen, 1985] work directly on the pixels using one image window as a template and search the second image for the best matching window. Most stereo matching techniques assume Lambertian surfaces (those where appearance does not change with the view point), which is not the case with most non-matt surfaces. Larger window gives better support for the matching, on the other hand the larger the window the larger the error from foreshortening (image neighbourhood of corresponding pixels look different in shape and size in the two images particularly for wide baseline and large angular motion) and from assuming that all points in the window have the same disparity. Using short baseline may solve the problem but it is impractical for large objects and it is also highly sensitive to noise.

2.3 Shape from shading (SFS)

SFS [Horn and Brooks, 1989, Zhang, et al, 1999, Durou et al, 2004] can be an alternative to add details to 3D image-based models. Although the method received a great deal of attention in computer vision research, it lacked success in determining absolute 3D shape of objects in actual applications due to its ill-posed formulation and unrealistic assumptions, such as the camera looks orthogonally at a Lambertian surface and there is only one single light source located at infinity. Formulation based on viscosity solutions can reduce the ill-posed problem [Prados and Faugeras, 2005]. Kovalevsky, 1997, suggested a SFS approach for polyhedrons with an initial triangular mesh. The Z-coordinate of each vertex of the mesh is then determined with a quadric function that forces the grey-level within each triangle to be constant, which creates an over-determined solution. Our approach has the same philosophy, but uses it on any shape that is described by any implicit function (planes, cylinders, etc) and computes only the deviation from that shape. A related technique, photometric stereo [Woodham, 1980] uses a fixed viewing direction while the light path is varied between successive images. This solves the under-determination of SFS. More reliable and precise results were obtained when both disparity and shading cues were used, by integrating stereo matching with SFS [Bulthoff and Mallot, 1988, Cryer et al, 1995, fassold et al, 2004, Vuong et al, 2006]. Some techniques use SFS to provide constraints for stereo matching [Scharstein and Szaliski, 2002, Worthington, 2002]. Here we use a technique that decides on which method to use for a given segment based on preset rules. Holes left after stereo matching, due to lack of textures or occlusions, are filled by a SFS technique that scales itself with data obtained by successful stereo matched points.

2.4 Mapping techniques for photo-realism

Besides standard texture mapping, there are several techniques developed to improve realism at the visualization phase at the end of the rendering pipeline. The idea is to *render* small-scale geometric details rather than pre-model them with sizeable polygon mesh. This is very efficient in memory use, takes advantage of graphics hardware, and can take into account the viewing direction. These methods, which vary in accuracy and size of produced details, increase the *perceived* geometrical details at runtime by adjusting pixel coordinates or normal directions, or both, to account for variation in surface bumps without increasing the complexity (polygon count) of the existing geometric model.

2.4.1. View-dependent texture mapping: Using a single texture image will surely include parts that are occluded, especially non-convex parts of the model, and will cause visual problems from many viewing angles. View-dependent texture mapping is a method that uses different texture maps with different view directions [Debevec et al, 1998, Magnor and Girod, 2000]. In this method, the displayed new view of a surface part in the scene selects the image that looks at this part from the direction closest to the desired new view. This gives a notable improvement to photo-realism and shows details visible only from certain viewing angles. The method is more effective if the model contains all the geometric details. Also, in order to prevent sudden transition during the animation, the different images must be blended or morphed together.

2.4.2. Bump mapping and displacement mapping: Even when proper texturing and lighting is applied, the rendered surface may look unrealistically smooth with no bumps or scratches. An improvement can be achieved by applying bump mapping [Blinn, 1978]. This is done by introducing per-pixel small variations in surface normal directions to add roughness and more realistic look to the lighted surface without the need to model each wrinkle as a separate element. However, since this is only a shading effect, flatness can still be seen on silhouettes. Another technique called displacement mapping [Cook, 1984] is implemented at the rendering phase by recursive subdivision (tessellation) of the initial model triangles then displacing the pixel coordinates of the created vertices. The displacement is carried out along the normal of the original surface according to a displacement map that is function of the textures. A variation of this approach, named view-dependent displacement mapping [Wang et al, 2003], considers the displacement as a ray-tracing problem and computes it as a function of the viewing angle, which allows for efficient rendering of self shadows and occlusions. However, this requires significant computation increase at runtime. Different implementations of bump and displacement mappings are included in most commercial rendering tools, and current graphic cards have some support for both. Our approach for adding the details, which happens at the modelling phase, is much simpler and requires less trials and errors and, although consumes larger memory, it avoids the extensive computations most mapping methods require during rendering. It is thus suited for real-time interactivity especially since huge models (hundreds of millions or even billions of triangles) can now be handled with advanced techniques that control the Level Of Detail (LOD) [Borgeat et al, 2005].

3. THE SEQUENTIAL MULTI-STAGE APPROACH

In this sequential approach the results from one stage guide the next. In the first stage, basic shapes are determined interactively while in the ensuing stages fine details are added automatically, on a segment by segment basis, using dense stereo matching and shape from shading. These techniques are used in a complementary manner. Selecting which one to use is done automatically based on preset logical rules. Since the techniques only need to compute the difference between the detailed model and the basic model, the approach works more reliably than standard techniques. We start by describing the main steps followed by some details of each.

3.1 The main steps

A simplified block diagram is given in figure 1, while figure 2 shows an example. The main steps are summarised as follows:

1- A small number of manually matched points are measured and used for image registration with bundle adjustment.
2- The object is segmented interactively into regions each includes a surface section or an object element.
3- An implicit function (e.g. plane, cylinder or quadric) is fitted to each segment using seed points.
4- A high-resolution mesh of triangulated 3D points is placed automatically on the segment based on its fitted function.
5- Using preset rules, the depth of the points in some segment regions is adjusted using stereo matching (figure 3).
6- For areas not meeting stereo matching rules, SFS adjusts the depth based on the intensity level (for example darker points are deeper into the surface and vice versa).
7- For symmetric and repeated parts, a copy and paste procedure is implemented.
8- View-dependent texture mapping is applied at rendering.

Details of some of the steps are given next.

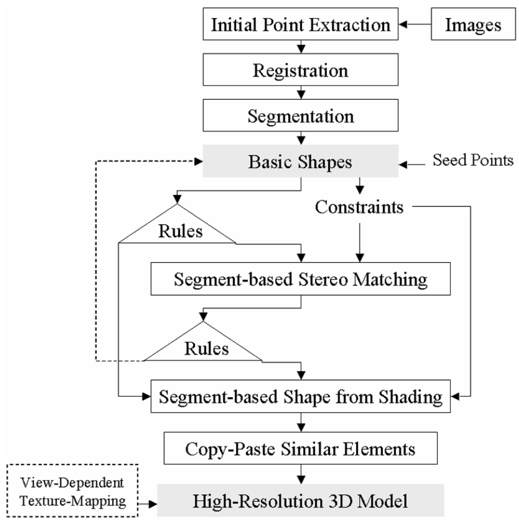

Figure 1: The general procedure for detailed IBM

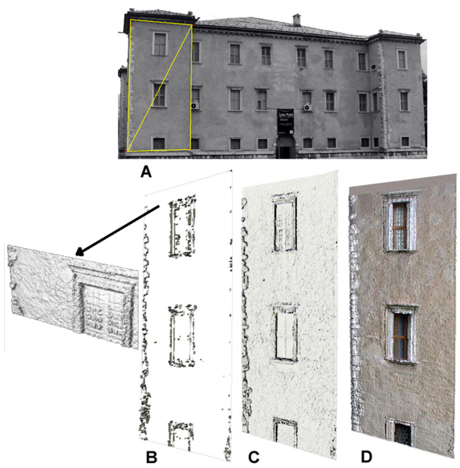

Figure 2: The sequential steps: A- basic model on left wall segment (a plane with 2 triangles); B- stereo matching results; C- added SFS; D) textured detailed model (400,000 triangles).

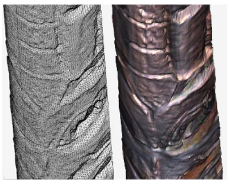

Figure 3: Adjusted vertices depth (on cylinder/totem pole)

3.2 Modelling of basic shapes

We first semi-automatically create basic models of surface elements such as planer walls, columns, windows, arches, or quadrics. For example, a column is automatically constructed after its direction, radius, and position have been automatically determined from four seed points, two on the corner of the top crown and two on the corners of its base. If desired, the ratio between the upper and the lower circle can be set, to less than 1.0, to create a tapered column. From this information, 3D points on top and bottom circles of the column can be automatically added to form the basic model. For windows and doors we need four outside corner points and one point on the window or door surface. By fitting a plane to the corner points and a plane parallel to it at the surface point, the complete window or door is created. Reconstructing arches starts by fitting a plane to seed points on the front wall. An edge detector is applied to the region and points at constant interval along the arch are automatically sampled. Using image coordinates of these points in one image, the known image parameters, and the equation of the wall plane, the 3D coordinates are computed. Details of the approach are given in [El-Hakim 2002]. The basic shapes, although can give a reasonable model when properly textured, will not be detailed enough for high-resolution photo-realistic visualisation. Dense stereo matching and SFS are used, each where best suited, to add fine details as described next.

3.3 The stereo matching approach

From the last step, we have a model consisting of basic shape segments, each with a fitted equation. A dense grid of points (can be every pixel) with 3D coordinates from the shape equation is created on each segment. We then apply a template-based stereo matching to adjust the coordinates of each point. This of course works best when sufficient texture variations or localised features are present on the surface. Therefore, the first rule we use to select the areas where stereo matching will go ahead is intensity-level analysis of the template window. This includes mean, standard deviation, and second derivative of the grey-levels of the pixels in the window. If those are higher than preset thresholds, the stereo matching will proceed otherwise we consider the region to be too uniform for stereo matching and switch to SFS, which works best on smoothly shaded surfaces. The stereo matching is based on minimizing the normalised squares of the difference between the template and the search window. The search is done along the epipolar line and we also limit the search to a disparity range computed from the basic model. For example in figure 4, point P1 in the left image has a corresponding point P2 in the right image that is computed directly from the basic model. Based on maximum depth variation (roughly preset), we can easily compute the region on the epipolar line (distance d) where we limit the search. The window in the right image is re-sampled to take into account the difference in orientation between the two images and surface orientation of the basic model. This accounts for the geometric variations between these two images and gives accurate and reliable results. We now apply another rule to accept or reject the matched points. If the best-matched window differs from the template by more than a threshold (pre-set experimentally), the matching is considered unreliable or invalid (e.g. the region is occluded in the right image) and the system reverts to the basic model point (point P2, figure 4).

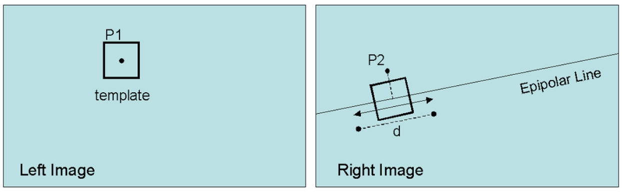

Figure 4: Matching with epipolar and disparity constraints.

3.4 The shape from shading approach

SFS is applied where grey-level variations are not adequate for stereo matching as discussed above (intensity analysis rules). We also use it on sections appearing only in a single image. Our SFS approach is applied to a work image: a grey-level version of the original with some pre-processing such as noise removal filtering and editing of unwanted shades and elements. We now adjust the coordinates of the candidate grid points (those not already altered by stereo matching) on the surface of the basic model according to shading using a curve describing the relation between grey-levels and depth variation from the basic model (figure 5). The curve intersects the grey-level axis at the average intensity value of points actually falling on the basic model. By adjusting the curve the results can be instantly reviewed. Combined with the stereo matching results, we now have a triangulated grid of points whose coordinates are altered from the initial basic model to account for the fine details.

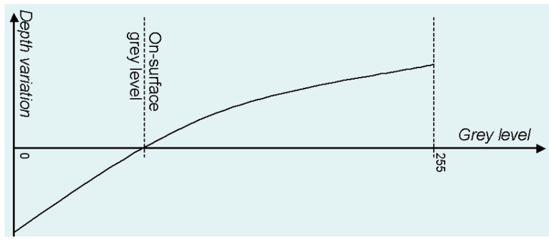

Figure 5: Grey level versus depth variation from basic model.

3.5. Creating reusable components

Our technique builds the model components - a surface segment or a combination of segments - to be reusable with other parts of the model or any other models similar in shape or symmetric, but may be different in dimensions. Although similar tools are available in commercial CAD and modelling software (such as the clone command in 3dsmax©) and some CAD modelling techniques [Nassar et al, 2003], we extended this idea to work directly on the images and perform accurate transformations and scaling using common points [El-Hakim et al, 2005].

4. EXPERIMENTAL RESULTS AND ANALSIS

We extensively tested our approach on hundreds of real data of different types to assess its effectiveness under real application conditions. Although, a detailed absolute accuracy of this type of results is difficult to evaluate since ground truth of the details are usually not available, the accuracy of the basic shapes from the interactive seed points has been estimated based on selected measurements. This accuracy ranged from about 1: 4000 to 1: 6000 for the created models. However, the main purpose of the tests was to evaluate the ability of the approach to capture fine geometric details to improve photo-realism with IBM. Various digital cameras with up to 8-mega-pixels were used. Examples of bricks and wood, stones or rocks, carvings, and architectural details are shown in figures 6-9. In the figures, the seed points used to construct basic shapes are displayed. Those were the only points measured manually (a process taking 1-2 hours per shown model), while hundreds of thousands of were added automatically to each model segment using stereo matching and SFS cooperatively as described above. The points were added at a rate of about 10,000 per second on a Pentium© 4, 3.2 GHz PC. User interaction was also required at the beginning to segment the surfaces, but no post editing of the model was necessary for any of the projects. One observation is worth mentioning. Since the technique relies fully on the calibrated camera parameters, both internal and external, to set up the various constraints, the procedure will not work well if the calibration is inaccurate or neglects lens distortions. On the other hand, the constraints allowed using a limited number of images by handling large baseline and rotation angles between images (up to about 75 degrees). Another limitation is that the surface must at least be approximated with an implicit function, so complex sculptures can not be modelled with this method.

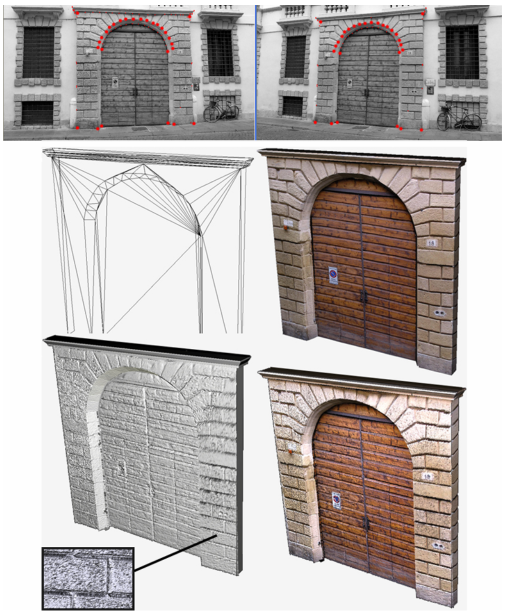

Figure 6: Bricks and woods example, stereo images with seed points (top) basic model (middle), and detailed model (bottom).

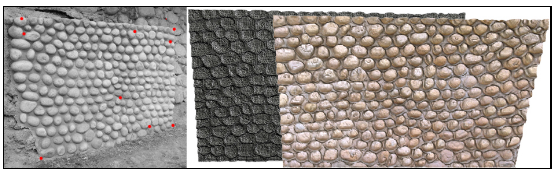

Figure 7: Example of Stones or rocks

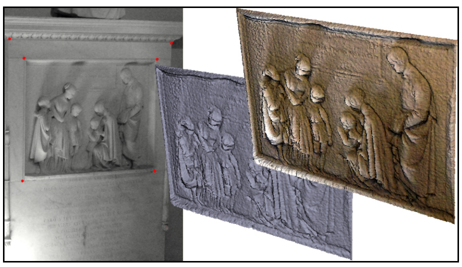

Figure 8: Example of carvings.

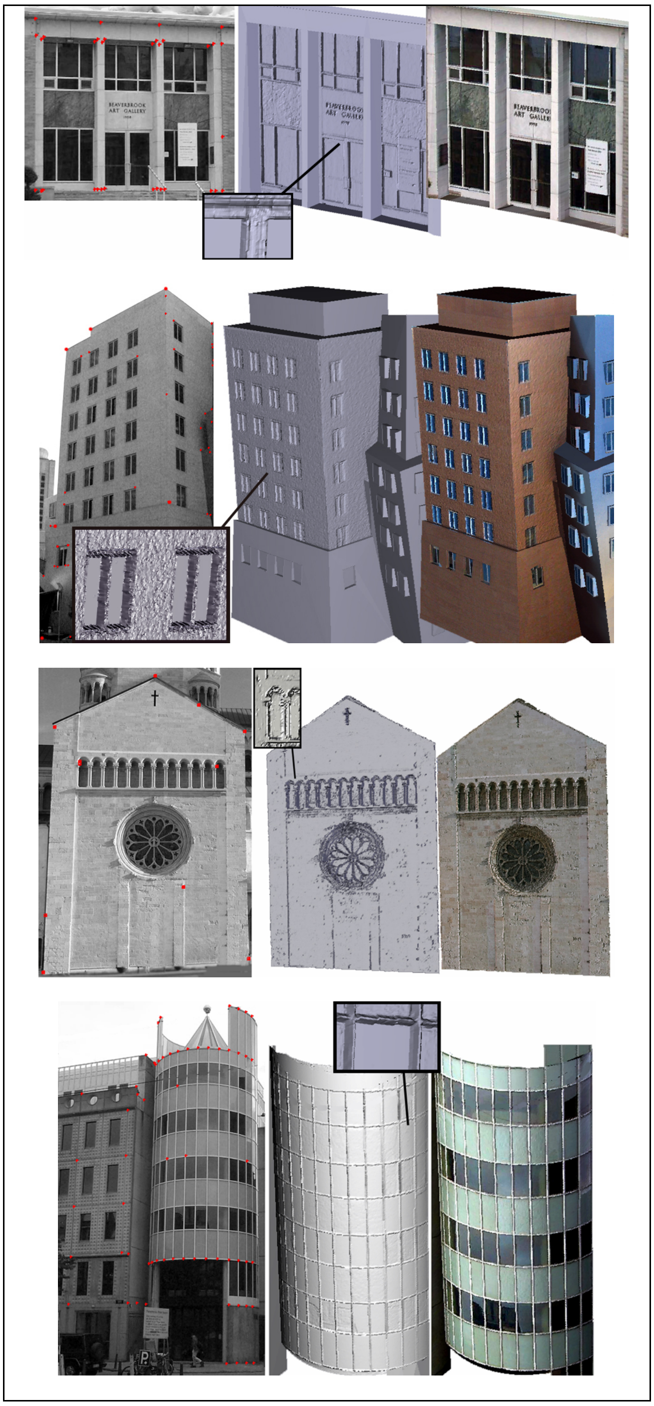

Figure 9: Four examples of different architectural details

5. CONCLUDING REMARKS

We presented a technique in the continuing effort to increase the level of realism and geometric details of image-based 3D modelling. The main contributions of our approach is that it creates the model in a sequential multi-stage segment-based procedure starting with basic modelling of surface elements then adding details with stereo matching and shape from shading, each where best suited. These techniques perform in a reliable manner since they capture the differences from the basic model rather than absolute 3D coordinates. The results have shown that the approach creates highly detailed models with no unpredictable behaviour and applies to many types of surface details. Wide baseline and large rotations between images were no problem unless they result in too many occlusions. Except for the measurement of strategically placed seed points, dividing the object into segments, and setting up some logical rules, fine detailed geometric models are created automatically. Since our approach is segment-based, overlaps or holes along common borders between the segments may appear after large depth changes. Techniques to cope with such problems to create a watertight model for those cases are now being developed. Automatic setting of the various thresholds is also in progress.

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