UVACAD: A SOFTWARE PLATFORM FOR 3D ARCHITECTURAL SURVEYING

Juan-Diego PEREZ-MONEO [a, *], Javier FINAT [a], Juan-José FERNANDEZ [b], Jesús. I. SANJOSE [b], José MARTINEZ [b]

[a] Research Group MOVIBAP. University of Valladolid. Spain
[b] Architectural Photogrammetry Laboratory. University of Valladolid. Spain

KEY WORDS: Close-range Photogrammetry, Cultural Heritage Surveying, Fusion of information, Points clouds, Software development

ABSTRACT:

Multirresolutions approaches require hybrid solutions for processing, analysis and visualisation of architectural and urban environments. Hybrid solutions must combine the accuracy of photogrammetric recording, density of point clouds captured with laser scans and increasing facilities provided by rendering of complex environments relative to reality-based 3d models. An efficient handling of the corresponding software tools requires the design and implementation of a global platform able of profiting the benefits of available software tools under a common environment. Along last two years and simultaneously to a very large amount of fieldwork (more than four thousand scans of different architectural styles and urban environments), the DAVAP Group has developed a software platform for a hybrid development and integration of surveying tools for dense clouds of 3d points and high resolution views. The performed hybrid strategy involves all phases of the well-known pipeline of processing clouds with the following contributions: 1) Data acquisition: High resolution views having approximately the same localisation (position and orientation) as the laser scan are incorporated; 2) Preprocessing: including the design and implementation of filtering algorithms for filling projections of dense clouds of points on orthoimages; 3) Registration: In absence of previous alignement on the site, it is necessary to identify the transformations between the different pieces to be merged, including the management of information arising from laser scans with different ways of representing the external world; 4) Integration for combining and merging the different pieces by using information for bounding surfaces (triangulation) or volumes (voxelization): Modelling and implementation of different strategies for simplifying clouds and octrees as superimposed structures in order to handle huge clouds; 5) Post-processing: Complete and reduce information of superimposed structures to dense clouds of points by filling holes and adaptive reductions of triangular meshes linked to importance functions. In this work we illustrate these principles with some applications concerning to small urban environments (an urban GIS for 4 villages of Palencia, Spain), the analysis of isolated buildings with Cultural Heritage interest (a large number of damaged churches, and castles), archaeological sites (the Roman city of Clunia), high-resolution hybrid models (interior of San Isidoro, Leon) and complex urban environments (Roman and medieval walls of Leon, Spain). A lot of work to be done concerns to an intelligent refinement or simplification, according to different importance functions, analysis for local recognition of 3d primitives, and volumetric segmentation. The interplay between strategies for integration (meshing and voxelixation) is a challenge for the next future.

1. INTRODUCTION

The increasing availability of 3D data arising from laser scans and the possibility of superimposing high resolution views pose new challenges for modelling, representation, identification and fitting of (geometric, architectural, urban) primitives on 3D objects in architectural and urban surveying. Basic discrete 3D data are given by dense maps of bits with additional radiometric properties (grey-level, color, textures). It is crucial the design and implementation of to simplify and lower the cost of 3D modelling for complex buildings or extended urban areas. This general goal involves all aspects of processing and analysis supported on 2d/3d information of high resolution views and dense clouds of points.

Some still outstanding problems concern to an efficient computer management of huge files and the extraction of (geometric, architectural or urban) primitives from discrete clouds of points. At the early nineties, there were a lot of techniques for the processing of image-based two-dimensional information arising from Photogrammetry and Computer Vision, but software tools for higher level analysis (3d Reconstruction or Recognition, e.g.) was more scarce or simply inexistent. Several strategies for these problems have been developed along last 20 years in image-based frameworks. Nowadays, some of these strategies are being adapted for range-based information in the UvaCad sofotware platform.

The development of this approach suggests the development of hierarchised hybrid strategies for the capture, processing and analysis of the available information. Hybrid methodology for 2d/3d data acquisition and registration uses strategies to some already well known strategies which are commonly followed in Photogrammetry and Computer Vision. Natural hierarchies for processing and analysis follow sampling strategies which are similar to multirresolution approaches, typical in 3D dense Reconstructions, but by taking advantage of a previous knowledge of dense depth maps arising from laser scanning.

An efficient handling of appropriate software tools for integrating different approaches requires the design and implementation of a global platform able of profiting the benefits of available devices, methods and tools under a common environment. Along last two years, the LFA-DAVAP group has developed the software platform UVACAD for the integration of processing and analysis tools in architectural and urban surveying. The resulting integrated system performs the fusion of geometrric and radiometric characteristics on a

---

* Ph.D.Student, Lab. 2.2, R+D Building, Campus M.Delibes, Univ. of Valladolid, 47011 Valladolid, Spain.

common 3D support. Two-dimensional digital information involves to cartographic, photogrammetric and computer vision sources. Analytic and synthetic three-dimensional information involves to laser scanning and Computer Graphics which can be related between them following a hybrid approach combining analytic/ synthetic on one side, and radiometric features with geometric characteristics on the other one. In this way, one achieves a 3D surveying, which is being applied for interventions planning and Augmented Reality.in archaeological vestiges(such as the Roman Theatre of Clunia (Burgos, Spain) or in large scale rehabilitation of degraded urban zones (Roman walls of Leon, Spain).

Figure 1. range-based Virtual Reconstruction of the Roman Theatre (Clunia, Burgos, Spain)

The main achievements of the current version of the software platform concern to the design and implementation of modules for the treatment and fusion of 2d/3d information contained arising from image and range scanning. Some Open Source libraries such as CGAL 3.2 for Computational Geometry and OpenCV for Computer Vision are incorporated for operations relative to the a basic management of 2d/3d information. Additional utilities which are specific for 3d files include basic projective operations (selection of slices and re-projections on planes selected by user), computation of triangular meshes, conversion to different formats (DXF, VRML, SCR) which are useful in different frameworks, basic geometric transformations for interactive visualization, consultation on original models or results arising from basic projective operations, superposition of adaptive octrees for a partial management of huge files (more than 50 millions of points), colouring of grey-level clouds of points by re-projecting high resolution views. Some beta versions of for the extraction of dominant planes and adaptive triangular meshes depending on geometric and radiometric properties are currently in proof, also. All of them include different kinds of parameters which are configurable by the user.

We have tested the software platform with a very large number of quite different examples along an intensive fieldwork (more than four thousand scans). Cultural Heritage examples include Archaeological Sites, a large number of different buildings and urban environments, which have allowed improving first results following hybrid (relative to inputs) and multirresolution (relative to outputs) approaches. Currently, the performed strategy involves all phases of the well-known pipeline of processing clouds with the following main contributions:
1.   Data acquisition: We have implemented several algorithms for the reprojection of radiometric information supported on high resolution views with approximately the same localisation (position and orientation) than the laser scan.
2.   Preprocessing: including the adaptation of Computer Vision algorithms for filling projections of dense clouds of points on orthoimages and lifting to the 3D model.
3.   Registration: In absence of previous alignment on the site, it is necessary to identify the transformations between the different cells to be merged, including the management of information arising from laser scans with different resolutions.
4.   Integration for combining and merging the different pieces by using geometric information for bounding surfaces (triangulation) or radiometric properties relative to cells as basic pieces for complex volumes (voxelization): Different strategies for simplifying clouds and octrees as superimposed structures in order to handle huge clouds.
5.   Post-processing: Complete and reduce information of superimposed structures to dense clouds of points by filling holes and adaptive reductions of meshes linked to importance functions.

2. RELATED WORK

2.1 Adaptive sampling clouds of points

The use of sampling for dense clouds of points is common in Computer Vision. Brute force algorithms are based in decimation.. Smarter algorithms in Computer Vision have RANSAC (Random Sampling Consensus) as paradigm [Fisher, 1981]. The RANSAC method has been applied to the estimation of epipolar geometry and motion. The original strategy of RANSAC is the identification of a maximal set of points which are consistent with a partial solution based on minimal set of points. Torr and Davidson (2003) have extended the RANSAC to a strategy IMPSAC (Importance Sampling and Random Sample Consensus), where the probability density of the camera parameters is propagated between different levels according to "importance sampling criteria". We have adapted the IMPSAC paradigm to range-based case, by introducing several importance functions linked to geometric or radiometric primitives in post-processing of clouds of points. Adapted sampling techniques use weights for probability functions which are inversely proportional to geometric properties (depth, difference of normal unit vectors) and radiometric properties (reflectantce).

2.2 Some contributions to modelling

The main novelty with respect to image-based methodologies concerns to the use of specific 3d methods linked to minimal surface elements (small triangles, typically) or volumetric elements (voxels), and their grouping in unordered meshes and maps of voxels. However, they follow a quite different approach even from the perception viewpoint: Meshes are centred on the object, whereas maps of voxels involve the whole scene and depend on the relative observer's position. Furthermore, usual triangular meshes are unordered, whereas cuboid voxel maps are totally ordered; thus, query processes follow a quite different methodology. These facts make difficult the information exchange between different 3d approaches, and consequently their combination for some basic outstanding problems. In order to apply strategies linked to different resolutions, it is important to decompose the scene, which can be performed by means the superposition of an iterative trihedral regiional decomposition or by identifying the structural elements which are prsente in the scene. Following the second approach it is necessary to achieve an efficient 3D segmentation (decomposition in a disjoint union of volumetric primitives). Some advances relative to the automatic detection of piecewise linear and quadratic elements are being currently integrated. .

3. HYBRID STRATEGIES FOR DATA ACQUISITION

Laser scanning can not intend by itself a complete covering of complex buildings or urban environments. Accessibility, self-occlusions and manoeuvrability impose serious constraints for data acquisition which can not be solved with standard laser scan devices. Terrestrial and aerial views provide additional information which must be processed for their conversion in a common format. There exist robust algorithms for views alignment or registering scans when the baseline is small and the overlapping area/volume is larger than thirty per cent. However, when some of precedent conditions is not fulfilled, a finer strategy is required. Some critical examples concern to 1) the management of views/scannings taken with different cameras/laser scan devices, 2) the accurate merging of interior and exterior models for small overlapping regions, 3) the overlapping of aerial views on 3d models extracted from image-based and range-scanning inputs. In this section we review some results relative to the three aspects.

3.1 Planning the acquisition with different image and range-based devices.

A careful planning must be performed for a maximal covering of the object to be surveyed. Some important cases are archaeological sites, isolated buildings and urban environments. The introduction of vertical elements as reference allows the selection of a reference plane. Diversity of devices for data acquisition and the unknown parameters forces to work in the uncalibrated case and, if it would be necessary, to perform an on-line calibration for cameras. In some exceptional cases (old bridge of Segovia, M30, Madrid, Spain, e.g.) we have used metric cameras. The compatibility between range-based and metric cameras poses some unsolved problems, due to the lack of information about internal calibration data of laser scan devices. In most cases, we have used the oriented metric model provided by laser scan as an Euclidean reference model for patching the information arising from image-based devices. Thus, the uncertainty is bounded by the error linked to scanning process.
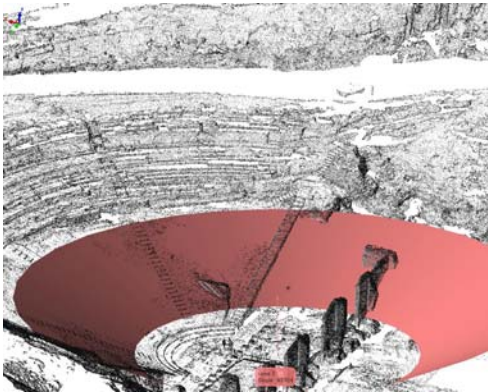

Figure 2. Fitting of geometric primitives to dense clouds of points. Roman Theater of Clunia (Burgos, Spain).

4. PRE-PROCESSING.

Pre-processing can be understood as the improvement of 2d/3d inputs for making easier their processing and analysis. A first merging and refinement of the available information is performed by using Polyworks (InnovMetric Inc). Post-processing concerns primarily to smart low-level 1) filtering (by deleting noise and redundant information), 2) segmentation or grouping (around geometric primitives and regions with locally similar properties) and 3) restoration (by filling holes, e.g.). All above processes are well-known in image-based approaches, but they are not standard in range-scanning. Thus, the performed strategy for a 3d hybrid modelling laser scanning imitates the approach based in high resolution views. Main novelties concern to the design and implementation of filtering algorithms for filling projections of dense clouds of points on orthoimages.

4.1 Filtering 3d point clouds

The main goal is the ellimination of redundant information, mainly in the overlapping regions presenting a higher density for the superimposed information. It is well known that the capture of 2d views is sensitive to radiometric and geometric properties:

• Strong reflectance variations: superexposed or sunny (resp. shadowed) zones give white (resp. black) saturation in grey-level intensity.
• skew orientations in narrow urban environments: a large number of views must be taken to be patched together in panoramic post-processing.

Both troubles can be corrected by taking different exposures from the same place and by equalizing the original views. The second problem can be solved even from a small number of views by performing an ortho-rectification (or at least a projection on a dominant plane). In both cases, radiometric and geometric properties are supported on the Segre product of two copies of the projective plane as the support for radiometric and geometric properties (see below, the section devoted to registration). The resulting model allows to compute the homography matrix up to scale (i.e. an element of fulfilling additional constraints) by a simply linear (indeterminate coefficients) method. The same philosophy can be applied for the 3d case.

To avoid artifacts (artificial roughness, e.g.) one can take two different kinds of strategies: increase the density of the point clouds (and consequently, the scanning time) or alternately, to perform an "intelligent reduction" along the data-capture process. Currently, the reduction can be performed in some laser devices, by selecting different windows for the same scene. This solution is not appropriate for post-processing. Indeed, the existence of different densities or the superposition of clouds on overlapping regions gives artifacts (nonexistent foldings or profiles, e.g.) in superimposed meshes and a not natural aspect (unexpected sudden changes in color or textures, e.g.) for radiometric properties. Thus, it is necessary a design of some kind of smart resampling adapted to the surface characteristics.

The starting point is the construction of a enough good triangular mesh. Delaunay triangulations are optimal in 2d plane, and tetrahedral Delaunay decomposition are also optimal in 3d space. However, it is not known an optimal triangular mesh for arbitrary surfaces in 3d space. There exist different candidates depending on hybrid energy functionals to be minimized; thus, one can expect only Pareto optimal solutions for linked multi-objective approaches. In Uva Cad platform variants of the Iterative Closest Point (ICP) algorithm relative to different kinds of sampling have been implemented. Huge clouds (several hundreds of millions of points) are decomposed in a disjoint union of cells by following an adaptive method based in succedssive octrees following a typical divide-and-

conquer algorithm. The resulting octree is linked to VRML files allowing the insertion of additional information for VR/AR applications.. Some additional issues relative to current developments concern to the automatic generation of superimposed structures to irregular distribution in clouds. Th eirregularity can be due to radiometric and geometric properties

• reflectance variations: lighter (respectively, darker) walls give high (resp, low) density point clouds, and sunny (resp. shadowed) zones give white (resp. black) saturation in grey-level intensity.

• Narrow urban environments: nearest zones have much higher density and skew profiles generate striated effects in clouds linked to the tangency locus of laser beams with regard to the object.
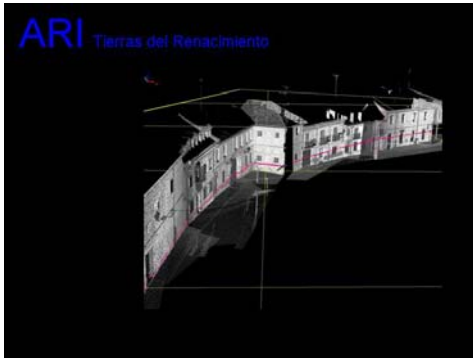

Figure 3: A 3D model for the half of a narrow street (Paredes de Nava, Palencia, Spain).

4.2 Alignement for grouping scans

The alignement of multiple scans is performed with the module IMAlign of Polyworks (InnovMetric). So, the whole set of data acquires a common reference in terms of a unique coordinate system. Some troubles appear for range-based multirresolution approaches based in scanning with different 3d laser devices. Some relevant multirresolution aproaches concern to

• The integration in the general 3d model of the "Capilla de San Pedro" in the Romanesque Monastery of Valbuena (Valladolid, Spain) of high resolution 3d models of medieval tombs. The general surveying of the Chapel is performed with an Ilris 3d, Optech, whereas the tombs are scanned with a Minolta 910.

• The generation of a 3d model for the interior of the early gothic Basilica of San Isidoro (Leon, Spain) which has been scanned with two range-based 3d laser scan devices based in quite different foundations (time of flight and difference of phase), with two different ways of representation (Euclidian and spherical coordinates) for reference systems.

• Portics of the Gothic Cathedral of Leon (Spain). We have performed the fusion of range-based information arising from TOF (Ilris 3D), pahse difference (Faro) and triangulation (Minolta 910) scanners..

Fusion of information has posed quite different problems. So,

• The existence of a common reference (Valbuena) object has allowed a fitting centered on common data (given by the boundary of tombs) which has been extended to the whole chapel giving a robust and virtually complete model.

• The information fusion for San Isidoro has been considerably harder. Indeed, the different ways of geometric representation an different responses to illumination conditions has forced the development of initial modifications of data for correcting radial distortion and saturated zones due to irregular illumination, before reprojecting on a common euclidian framework. Such corrections involve to calibration and restoration issues. Hence, the identification of transformations to be done for merging scans taken with different laser scan devices involves geometric and radiometric aspects.

• The surveying of portics of the cathedral of Leon are inked to the development of an Information System with web facilities for a collaborative work is referred to multi-dimensional database which is referred to 2D/3D information for navigation, identification of damages and different proposals for interventions

Some general problems for the fusion of spherical and euclidean representations are linked to the availability or not of 3D information. Indeed, self-occlusions are larger for the spherical-based laser scan than for euclidian-based laser scan. Thus, differences between global models are meaningful for extracting the whole geometry of the model.

5. REGISTRATION:

Registration in image-based photogrammetry concerns to the accurate determination of coordinates for control points. Usually, it is performed manually (distanciometer, teodolite, e.g.) or semi-automatically (based in total station) for higher amount of related points. After correcting distortions (if there were on) for ordinary cameras, the registered information is applied for computing the algebraic transformations between pairs of views. This process is applied for merging different oriented views in 3d models with a small baseline. Bundle adjustment provides the most common method for patching together common data in Photogrammetry and Computer Vision community research. To minimize errors, it is convenient to take a redundant number of control points. Furthermore, complex objects (façades, sculptures, e.g.) can require dense information, where scanner devices have a larger advantage with respect to traditional image-based approaches.

Often, a large number of view/scan captures is performed without a previous registration of control points. The global orientation between scans each other can be determined from a (natural or added) vertical element taken as reference line from the beginning. Every scanning is oriented with respect to such a line. In absence of previous alignment on the scene or the object, it is necessary to identify the transformations between the different pieces to be merged. The existence of a common vertical element allows reducing the problem to well-known planar transformations; in the euclidean case, one has a one-parameter transformation and a very fast convergence is guaranteed.

Some additional troubles appear in trying of matching skew views or when the dense clouds of points arising from laser scans with quite different densities and ways of representing the external world. Matching of skew views is solved by the application of Computer Vision algorithms (between 4 and 8 points depending on the views). The use of different laser scans (time of flight and phase difference) require some additional transformations between euclidian and spherical coordinates for

representing the external world; currently, we are working on a vector approach to minimize rounding errors.

6. INTEGRATION.

The management of 3D huge clouds of points require software tools with high performance for modelling, representation and active interaction from the user. The increasing performance of software tools allows an information transfer between low-level superimposed structures supported on clouds of points and high level design and management tools. Matching of different scans generate files with tens of millions of points. The global management of such huge clouds is not practical from the computational point of view. Two common strategies for the management of huge clouds of points are iterative subdivisions or sampling.

6.1 Subdivision following octrees

Usual subdivisions of huge unordered clouds of points are given by octrees. The original cloud is decomposed in a disjoint union of subclouds bounded by a triply orthogonal systems; each subcloud is contained in a cell which is labeled as void, if the number of points inside is lesser than a threshold fixed by the user. The set of cells of an octree is a partially ordered set; thus, octrees simplify query processes (following ICP algorithms, typically) and the construction of superimposed structures (triangulations, typically). Parallelization increases the performance of both processes. The main problem is the design and implementation of merging algorithms for partial triangulations corresponding to the subclouds inside of adjacent octree cells. The main steps are: duality for each partial 3d Voronoi diagrams (3VD), merging of partial 3VD (following a similar idea to divide-and-conquer algorithm) and duality again to recover a matched triangulation. Due to the lack of space, details are omitted.
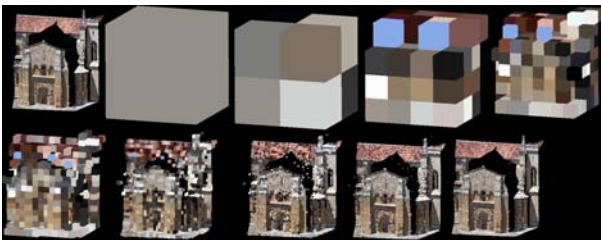

Figure 5: Superposition of an octree for the management of huge clouds of points.

6.2 Sampling for multirresolution approaches

In visualization of complex scenes, it is convenient to work with different resolution levels: Fine for the foreground, and coarse for the background; this issue can be solved with an importance function for sampling linked to the relative depth (see above for details). The visualization of navigation resamples optiionally the original cloud by means of the contraction/expansion of the original cloud according with coarse decimation strategies. The resulting global model preserves the topology of structures linked to the original clouds, i.e., the shape connectivity even for a coarse global model.

A general coarse-to-fine multi-resolution approach strategy is based in sampling strategies, which can be locally refined by selecting the appropriate 3D cells. Multi-resolution strategies are based on sampling the original cloud in blind (successively decimating, e.g.) or in adaptive strategies depending on geometric or radiometric criteria (see above).

After sampling, a grouping strategy based in a variant of the ICP (Iterated Closest Point) algorithm is developed. Following the selection of the pair of closest points for each sampled point, the plane corresponding to the triplet is identified. The algorithm propagates with respect to the nearest triangles, examines the MPR or Maximal Planar Region (above a threshold), identifies the winner MPR, computes the local transformations between adjacent MPR and applies it to data shape. The propagation is allowed whereas the unitary normal vector is similar (modulus a threshold). Otherwise, the query stops and returns a polygonal planar region not necessarily a simple on (there can appear holes inside. In this way, a collection of small planar regions is generated as candidates for the support of dominant planes. The identification of dominant planes allows solving the algebraic transformations between adjacent maximal planar regions, and the global information management of structures linked to the original huge clouds.

7. FUSION OF INFORMATION

Most of conventional laser scanning devices can not provide a complete information of complex objects or scenes. Some problems are related with self-occlusions, alternating concave and convex regions, false positive in filling holes with superimposed meshes, misuse of data linked to sampling procedures, etc. Thus, an active supervision is need for correcting (completing or reducing) information corresponding to superimposed structures to dense clouds of points. Main strategies are linked to adaptive refinements or adaptive reductions of meshes which can be managed in terms of importance functions, also.

7.1 Completing information

Often, the information is not good enough for supporting ornamental or texture details which are contained in high resolution views or panoramas. This issue can be solved by reprojecting onto the cloud high resolution views. Adaptive refinements are based in a reprojection of rectified high resolution views or panoramas on the global cloud. When radiometric properties have not true color (grey level intensity or false color), the reprojection of colored pixels on screens with almost the same orientation improves the quality of visualization, recovers 3d textured surfaces, and inserts additional points between the available pixels arising from the scans.

Figure 6: Reprojection of high resolution views on complex façades (Santa María de Arbás, León)

From a practical viewpoint and to minimize errors in reprojecting color and textures, it is advisable to take views with similar orientation for laser scan and high resolution images.

7.2 Filling holes

A blind policy of filling holes can modify in a substantial way the nature of the surveyed object from scanning and viewing, after rectifying high resolution views. Furthermore, sometimes it is not possible to perform scanning from the high. Classical solution consists of inserting additional points on an augmented mesh obtained from some kind of refinement (interpolation, e.g.) from the original triangular mesh. This procedure can alter in a severe way the object geometry and its topology (by modifying its connectivity, e.g.). An alternative low-cost approach consists of incorporating additional pixels obtained from a large number of views. Pixels are reprojected for each orientation of the cloud, including aerial high resolution views (captured with aerostatic devices, e.g.). However, the reprojection of high resolution views on 3d models poses some issues to be solved related to robustness and quick convergence, Both issues are already solved for small baseline and similar orientation with respect to the scanning. In the general case, is necessary to develop a strategy for reprojection similar to the general projective framework developed in 3d reconstruction from several views in presence of strong difference for camera localizations.

In the following figure, we give an example of combination of strategies such as correction of radial distortion, hole- filling by morphological operators and color reprojection. reprojection of coloured textures on the bridge of Segovia (M30 street, Madrid, Spain).

Figure 7: Puente de Segovia, M30 (Madrid, Spain).

The reprojection must be performed after correcting the distortion to prevent a lack of definition of true profiles.

8. CONCLUSIONS AND FUTURE WORK

A software platform in C++ has been developed for integrating range- and image-based methodologies in a common hybrid and multirresolution framework. Software tools of Computational Geometry, Computer Graphics and Computer Vision are included in a common framework with applications to architectural and urban surveying, Civil Engineering and different topics related to Cultural Heritage. A lot of work remains to be done. In particular, the reprojection of planar boundaries contained in 2d views to true 3d contours through a meaningful number of control points is a challenge for the next future.

9. REFERENCES

[Allen:2003] P. K. Allen, I. Stamos, A. Troccoli, B. Smith, M. Leordeanu and S. Murray: New Methods for Digital Modeling of Historic Sites. *IEEE Computer Graphics and Applications, Vol 1* Sep. pp. 32-41.

[Bos04] G. Bostrom, M. Fiocco, D. Puig, A. Rossini, J. G.M. Goncalves, V. Sequeira. Acquisition, Modelling and Rendering of Very Large Urban Environments. *Second International Symposium on 3D Data Processing, Visualization and Transmission.*(2004) Vol31. pp.191-198.

[Cur96] B. Curless AND M. Levoy. A Volumetric Method for building Complex Models from Range Images. *Proc. SIGGRAPH '96* (1996). Vol30. pp. 303-312.

[Fis81] M.A. Fischler AND R.C. Bolles. Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image. Analysis and Automated Cartography. *Communications of the ACM*, Vol.24, 6, (jul-1981). Pp.381-395.

[Gel03] N. Gelfand, L. Ikemoto, S. Rusinkiewicz, M. Levoy: Geometrically stable sampling for the ICP Algorithm. *Proc. 4th Intl Conf on 3D Digital Imaging and Modeling.* (2003) Vol 31, pp.117-126.

[Gel05] N.Gelfand, N.J. Mitra, L.J.Guibas H.Pottman. Robust Global Registration. *Proc. Symp. Geom. Processing, Eurographics*, 2006 (M.Desbrun and H.Pottman, eds. Vol31, pp. 117-126.

[Mor00] D.D. Morris and T. Kanade: Image-Consistent Surface Triangulation. *Proc. Computer Vision and Pattern Recognition.* (1997). Vol 1. pp.332-338

Acknowledgements