3d Object Reconstruction from a Single Image

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Abstract

This paper describes the photogrammetric techniques and approaches developed for 3D object reconstruction based on a single image. It is possible to get metric information from a single view when the stereo-based photogrammetric technique is not available. In this scope some advanced multidisciplinary techniques which allow an automatic capture of meaningful elements for perspective models from a single image are discussed.

Keywords: Photogrammetry, Single image, Vanishing point, Robust estimator, 3D reconstruction

Introduction

Photogrammetry has been dealt with the precise three-dimensional (3D) reconstruction of objects from images for many years. Generally the 3D reconstruction of objects can be performed using stereo image pairs. The primary approach for 3D object reconstruction using 2D images (photographs) is based on a bunch of overlapped images in close-range photogrammetry. Recovering a complete, detailed and accurate 3D model from images is still a difficult task if uncalibrated images are used. Additionally precise calibration and orientation procedures, which are all based on manual or semi-automated measurements, are required. To our knowledge there are also some approaches that perform a fully automated 3D reconstruction of the objects from oriented images. Although close-range photogrammetric techniques provide the most complete, flexible and accurate solutions sometimes it is not possible to obtain these stereo-images especially when working in places with difficult access and coverage limitations are difficult to overcome. In such situations when only single photographs exist there are some possibilities to obtain 3D reconstruction from the original object. As widely known it is not possible to provide metric information and 3D object

reconstruction from a single image except some special conditions. From a single view, it is however possible to extract substantial information about the object and even to reconstruct the 3D model. In these sense multidisciplinary approaches such as photogrammetry, computer vision and computer graphics have provided an ideal synergetic frame. There has been several studies which address the problem of 3D reconstruction from a single photograph. Some studies develop a reconstruction system from single images, exploiting user-selected edge features to build a model from 3D primitives and then verifies its accuracy by projecting the model back into the original image. There are some studies to investigate the reconstruction of 3D models from line drawing assuming geometrical constraints provided by the location of vanishing points (VP). There are some methods for reconstructing polyhedral object models from a single view. These methods use measurements of image lines, object information as well as topology and geometric constraints (parallelism, perpendicularity). Some approaches do not need models of the object nor known internal camera calibration. Neither use vanishing lines or VPs. In this sense, several types of constraints based on topological relations and

basic primitives are established (Aguilera, 2009; Debevec, 1996; Liebowitz et. al., 1999; Heuvel, 1998; El-Hakim, 2000; Criminisi et al., 1999). It should be noted that 3D reconstruction from a single view is a difficult task because of intrinsic complexities (ill-conditioning) which increase with the scale. In this study an overview of the techniques 3D reconstruction from a single image is given and photogrammetric processes of a single image are explained in detail with the aid of a software (sv3DVision) developed for the 3D reconstruction (Aguilera, 2005).

Technical Processes of 3D reconstruction from a single image

It is possible to acquire metric information about the objects and even to reconstruct a realistic 3D model from a single image. One of the most critical point in this process depends on identification, with a high precision and reliability, of its structural elements (i.e. vanishing lines and points). These elements constitute the framework that supports the whole process as they provide independent geometric constraints which can be exploited in

several ways: from camera self-calibration to its own 3D reconstruction and visualization.

One of the most crucial steps in the metric analysis from a single image refers to detecting structural elements with high precision and reliability belonging to an oblique image. Man-made objects are often present in the scene, therefore features like straight lines and angles can be used to acquire information about the camera or the 3D structure of the captured object. Nevertheless, this is not an easy task, considering that usually images contain radial lens distortion. Thus, although several algorithms based on image processing exist currently, some hierarchical and hybrid approaches will be required in order to guarantee quality. Unfortunately, a universal method for automatic vectorization does not exist. In this context some advanced approaches have been developed; i.e. Canny filter can be applied to detect vanish lines; a line-growing algorithm called the Burns detector can be applied for vanishing lines extraction; or a parameter space based on Hough transform be used for detecting vanishing lines automatically.
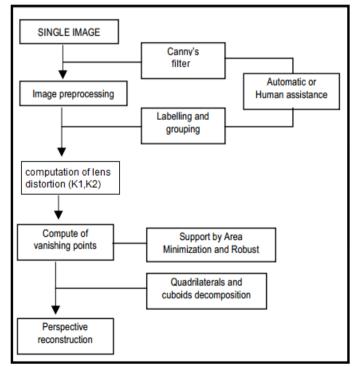

Fig. 1: Methodology (adapted from Aguilera et al. 2004)

Vanishing Point (VP) Detection

Reliable and accurate 3D reconstruction depends strongly on a robust estimation of VPs. VPs are computed from bundles of perspective lines in the framework of projective geometry. VPs arise from the intersection of a bundle of parallel lines in the scene, which become perspective lines in its representation. Therefore VPs are traditionally estimated from intersections of hypothetic perspective lines or by minimizing the distance to projections of parallel lines. Both procedures are not robust ones, and errors are not suitable for photogrammetric applications. Then a sophisticated method is needed in order to obtain more accurate results.
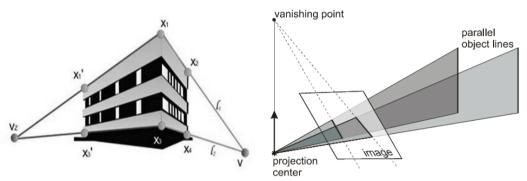

Fig. 2: Vanishing points of parallel lines. The points $\mathbf{x}_i$ constitute the reference plane (Heuvel 1998).

A robust and accurate identification of VPs allows to superimpose in an automatic way a perspective model on the view by taking in account the intersections of bundles of coplanar perspective lines. The line through two VPs is a vanishing line. In the same way, a vanishing plane contains 3 non-aligned VPs. There are several camera calibration approaches exploiting the presence of VPs in close-range photogrammetry as well as in computer vision.
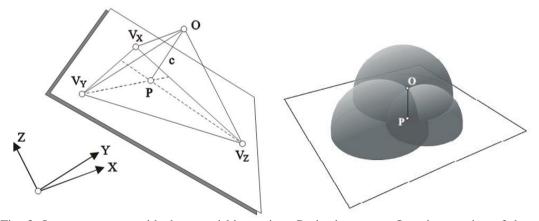

Fig. 3: Image geometry with three vanishing points. Projection center O as intersection of three calibration spheres and principal point P as its projection on the image (Grammatikopoulos et al. 2004)

The intrinsic or interior orientation parameters (i.e. the focal length, the principal point, the lens distortion) are recovered automatically based on VPs geometry and image analysis. The orthocenter of the triangle (Fig. 3) formed from the three VPs, Vi, of the three mutually orthogonal directions identifies the principal point, P, of the camera through the cross product of the segments of the triangle and its heights (Aguilera and Lahoz ,2009;

Grammatikopoulos 2006). All possible locations of O in the 3D image space form a sphere (or calibration sphere) and the projection sphere is defined as intersection of three calibration spheres. The radial lens distortion parameters (k1,k2) are estimated exploiting the presence of short segments (mini-segments) through collinearity condition. This estimation is performed only with line segments that satisfy the orientation constraint. As explained the vanishing point is found as the intersection of the interpretation planes associated with the image lines and the image plane (Fig. 4, on the right). In case of parallelism of image plane and object lines the VP is at infinity. To avoid this singularity, the vanishing point can be defined as the intersection of the interpretation planes and the Gaussian sphere (Shufelt, 1996). Some of the vanishing point detection techniques use a Hough transform approach in which the parameter space is located on a so-called Gaussian sphere (Lutton et al., 1994).

Single image geometry: The extrinsic (or exterior orientation) parameters, that is, the perspective rotation matrix (camera orientation) and the translation vector which describe the rigid motion of the coordinate system fixed in the camera are estimated. (Fig. 4)
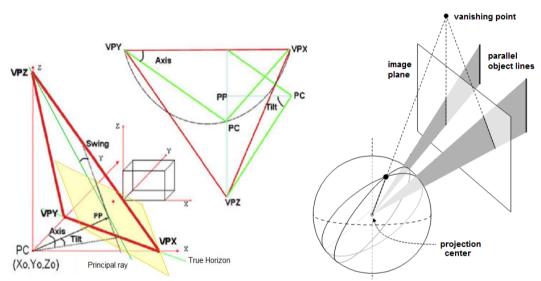

Fig. 4: Exterior camera parameters from a single image (Aguilera 2009), vanishing point on image plane and Gaussian sphere (Shufelt 1996)

These rotation angles use the "axis, tilt and swing" to define the rotation of object-space to image-space. The axis is a clockwise rotation about the Z axis (nadir direction), and is the angle between the object-space Y-axis. The tilt angle is a rotation about a line parallel to the true horizon line, and is the angle between the principal ray (image plane normal) and the line from the principal point to the Z vanishing point. The swing angle is a rotation about the image z-axis and is the angle between the positive image y-axis and the trace of the projection of the principal plane (Fig. 4). The translation vector, that is, the absolute camera pose is estimated based on some apriori scene information, for example, a distance together with a geometric constraint defined by the user (Aguilera and Lahoz , 2009). The reference frame for the camera pose estimation is defined with relation to the scene geometry based on a local coordinate system. The robustness of the method depends on the precision and reliability of VPs computation, so the incorporation of robust estimators is needed.

Robust estimators for VP detection

Robust methodology can be used for VP detection in order to provide a robust structure of the 3D scene. Robust estimators provide an adjustment method, and detect wrong observations appearing as outliers in an

efficient way. Robustness corresponds to their independence with respect to the errors distribution. These estimators are based on applying variable weight functions which allow to modify original weights in order to reject observations having blunders errors in the adjustment (Aguilera et al. 2005). Some different robust estimators have been used for robust estimation of vanishing points, ie. Danish method, Minimal Sum, Huber,. The main goal of all of these methods is the automatic elimination of lines which are not adequate for the "true" determination of vanishing points. The rightness should be measured in terms of the area minimization. RANSAC (Random Sample Consensus), an algorithm for robust fitting of models in the presence of many outliers, has been adapted to vanishing points compute in order to detect blunder vanishing lines. Some advanced variants of RANSAC methods have also been developed (Table 1) (Aguilera et al. 2004).

Table 1 Robust estimators

Danish estimator	German&McClure estimator	Minimum Sum estimator	Huber estimator	
$W(v) = Exp(-\mid V(i) \mid^2)$	$W(v) = \dfrac{\psi(v)}{v} = \dfrac{1}{(1+v^2)^2}$	$W(i) = \dfrac{1}{\mid V_i \mid}$	$W(v) = \begin{cases} 1 & \text{for} & \mid v \mid / \sigma \leq a \\ \dfrac{a}{\mid v \mid / \sigma} & \text{for} & \mid v \mid / \sigma > a \end{cases}$	

RANSAC robust estimator can also be used for clustering segments according to their correspondence with the three basic vanishing points directions. Segments are clustered through an iterative process based on their colinearity, taking an orthogonal distance as input parameter or threshold (Fig. 5). Those segments, whose orthogonal distance is lower to the established threshold, will be clustered as collinear segments. This step can be performed through RANSAC that incorporates slope analysis as a voting criterion, allowing the detection of possible outliers (wrong vanishing lines) during the clustering process. The application of RANSAC together with the inherent geometrical constraints in vanishing points (perpendicularity etc.) allow to carry out a clustering of the segments.
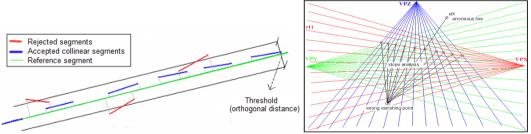

Fig 5. Clustering of segments and slope analysis based clustering with RANSAC (Aguilera et al. 2005)

Modified Gaussian sphere methods have also been used for the estimation of the vanishing points as well as detecting the most relevant wrong vanishing lines. After detecting the most representative wrong observations, an iterative re-weighted least square adjustment can be applied supported by the triangle area minimization method (Fig. 6) and Danish M-estimator. The method consists on minimizing the triangle surface composed by each extracted segment and the corresponding vanishing point, so that the sum of each triangle's area will be minimized. M-estimators aim to detect and reduce the effect of outliers.
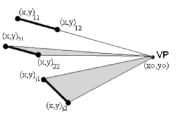

Fig. 6: The method of triangle area minimization (Aguilera et al. 2005)

Experiments: In order to determine the advantages and limitations of the approaches explained before, a flexible software sv3DVision (developed by D.G. Aguilera) is used in the experiments. This software, developed for the 3D reconstruction and visualization from a single view, was designed for educational and research purposes. On the other hand, sv3DVision incorporates several robust and statistical techniques in order to guarantee reliability in the automatization of the process. An original single image used in the experiment is shown in the Fig.7. Canny's filter algorithm is used for edge detection over the building with a regular reliability. Segments in vanishing lines are clustered with RANSAC algorithm for VP computation (Fig. 7). The main feature of the software is its hydrid character since combines several of the approaches (i.e. photogrammetry, computer vision, computer graphics, robust estimators) for 3D reconstruction. Additionally a realistic and accurate visualization of 3D object scene can be generated automatically. It is possible to work directly with VRML files in order to create, edit and visualize 3D virtual models. General view of the software and some estimation results (computed VP coordinates, calibration and orientation angles) for the single image are illustrated in the Figure 8.

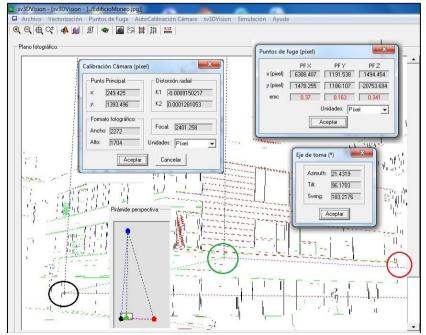Fig. 7: Original single image (left), segmentation and clustering of vanishing lines (right)

Fig. 8: General view of sv3DVision software and some estimation results for the single image

3-Dimensional Analysis

Useful information can be extracted from the perspective geometry of imagery containing man-made objects. As mentioned before it is not possible to provide a 3-dimensional analysis of the object from a single image alone. To do so, one also needs either a second image of the same object taken from a different place or additional information about the object for example, geometric constraints and image invariants. For man-made structures, geometric constraints on the object perpendicularity, coplanarity, parallelism, and so on and image invariants distances and angles can be used to solve the dimensional analysis problem from a single image. The object coordinates of a point P are usually recovered by means of the collinearity model given below. (The collinearity condition states that a point in object space, its corresponding point in an image, and the projective center of the camera all lay on a straight line.) Therefore, the entire dimensional analysis problem could be reduced to the problem of computing the coordinates of the object through the collinearity condition (Table 2).

Table 2. Dimensional analyse formulas

$$X = X_0 + (Z - Z_0) \cdot \frac{r_{11}(x - x_0) + r_{12}(y - y_0) - r_{13}f}{r_{31}(x - x_0) + r_{32}(y - y_0) - r_{33}f}$$

$$Y = Y_0 + (Z - Z_0) \cdot \frac{r_{21}(x - x_0) + r_{22}(y - y_0) - r_{23}f}{r_{31}(x - x_0) + r_{32}(y - y_0) - r_{33}f}$$

Once the camera model has been estimated, a dimensional analysis of the object based on distances, angles, and surface areas can be performed. Moreover, this step constitutes a final validation of the accuracy of the analyzed model, taking into account that the results have been compared with other surveying measurements, such as topography and terrestrial laser scanners. From the reliability perspective it should be noted that the obtained standard deviations of object coordinates are (5-10 cm) level in 3-D analysis from a single image. This result is naturally lower than the accuracies obtained from stereo pairs in photogrammetry technique.

Conclusions

Generally stereo-based close range photogrammetry technique is used to get metric information from the images with high precision and reliability. Sometimes it is not possible to obtain multiple images and only single photographs exist. It is possible to get metric information from a single view with an acceptable accuracy when the stereo-based photogrammetric technique is not available. In this scope some advanced multi discipliner approaches which allow an automatic capture of meaningful elements for perspective models from a single image are discussed. The study shows the importance of synergic integration of other disciplines (computer vision, computer graphics, robust estimators, etc.) to provide an advanced research frame for future work.

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