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Historical photography-based computer-aided architectural design: Demolished buildings information modeling with reverse engineering functionality

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ABSTRACT

This paper is about single three-point perspective historical photography-based CAAD modeling (amateur camera calibration, pose and 3-d reconstruction) of man-made environments, buildings and monuments, rich in geometrical regularity. The proposed method, gains profit from the presence in the image (historical photography) of three vanishing directions and two orthogonal object edges with known length ration, and then focuses on the graphical estimation of the *skew intrinsic parameter* of the uncalibrated camera (i.e. the angle of *dot*'s *x* and *y* optical axes, in photography plane), dealing in this way even with the skew presence case (non-rectangle *dot*). The presence of skew is not a negligible factor in historical photography of early 20th century years, due to *dot* optical axes failure (carelessness manufacturing) or collapse, as well as the twist effect (distortion) from the undocumented film development process in 1920s. The graphical recovery of the *skew factor* is the main contribution of the paper to the pose and CAAD literature. It is shown that a single three-point perspective amateur photography, even with the presence of skew, is adequate for calibration, pose and planar structure (building façades) recovery, if the usual in building's architecture geometric clues are present (i.e. planarity, orthogonality and parallelism) and some metric data (e.g. length and width of demolished building's dimensions) are available. The proposed method was validated on a simulated cuboid and demonstrated on a number of demolished historical buildings for which only one uncalibrated (and skewed) photography was available. The accuracy evaluation shows that the method is suitable for CAAD modeling applications regarding demolished buildings and monuments of the early 20th century years (2% relative accuracy, i.e. 40 cm for a 20 m façade, included the metric data inaccuracy). The method is of interest for architecture, archaeology, reverse engineering and virtual reality.

1. Introduction

There are many reasons and motives for 3-d modeling of real-world objects, buildings and scenes, including: virtual reconstruction of historical buildings and monuments that no longer or only partially exist [1]; digital documentation of historical buildings and monuments for restoration purposes in case of fire, flood, war, earthquake, etc.; ability for virtual interaction without the risk of damage; production of e-learning data for educational resources; virtual tourism; virtual museum exhibits; and interactive on demand 3-d visualization of the object, building or scene.

3-d model based applications include: digital documentation of buildings, monuments and sites [2,3]; robot navigation and obstacle recognition [4]; augmented and virtual reality; architectural surveying; computer games; virtual tourism; forensics and inverse camera sciences [5].

In general, most of these applications specify ten requirements: high geometric accuracy; user-friendly interaction environment; all details capturing; quality photorealism; virtual video-on-demand; high automation and low user interaction; portability; low cost; model size efficiency and application flexibility. The order of importance of these requirements depends on the application's objective. So, for digital documentation applications the *geometric accuracy* and the *all details capturing* are at the top of these requirements, whilst for e-tourism and e-culture special care must be taken for *virtual video-on-demand* and *quality photorealism*.

A single system that can satisfy all these ten requirements is still in the future. In particular, accurately capturing all details with a fully automated system for a wide range of objects remains elusive, as well as elusive remains a system for 3-d virtual reconstruction of demolished buildings, when only one uncalibrated photography is available and the building capturing geometry is not rich enough. Please, refer to Sabry F. El-Hakim et al. [6] and Paul E. Debevec et al. [7] for the geometry, image and range-based available 3-d modeling techniques, as well as for some hybrid and multiple techniques.

The current article addresses (into the image-based modeling domain) the problem of single uncalibrated historical photography-based 3-d modeling of buildings that display a number of properties of geometric clues (*planarity, parallelism, orthogonality, symmetry* and

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planar or *space topology*), such as the man-made architectures, buildings and monuments rich in geometrical regularity. This historical photography usually is just a single analogue photograph or a post-card which, nearly always, was captured from an uncalibrated camera for which the skew *intrinsic* parameter (i.e. the angle of the *x* and *y* optical axes of the *dot* in photography plane) is unknown. The knowledge of skew factor's value is essential for the evaluation of the *camera projection matrix* and its graphical recovery is the main contribution of the paper.

The presence of skew is not a negligible factor in historical photography of early 20th century years, due to *dot* optical axes failure (carelessness manufacturing) or collapse, as well as the twist effect (distortion) from the undocumented film development process in 1920s [63].

The graphical estimation of the skew *intrinsic* constraint is based on modern and effective CAD tools (i.e. a virtual camera embedded in a CAD platform and an open software design environment) for a controlled simulation of the photography projection procedure. These tools (virtual camera and open software functionality) are available only on today's modern CAD software controlled environments.

Modern and more effective CAD tools could assist architects and engineers, and the affordances they provide change the practice of modeling itself suggesting fundamentally new ways of thinking about the domain (virtual and augmented reality, design and engineering) [8–10,34,60,61].

1.1. Current approaches

The classical problem in the image-based techniques is to reconstruct the metric structure of the scene from two or more images by stereovision techniques [11,12]. However, this is a hard task due to the problem of seeking correspondences between different views (time-consuming and costly). Also, these techniques are not applicable in cases where only one, calibrated or not, image is available.

Methodology for 3-d modeling from multi or single images, when specific restrictions are applied, is by default *constraint-based* and it tries to exploit geometric knowledge (properties) of the scene clues, like orthogonality, planarity, etc. Geometric properties are either detected automatically [13–15], or they are user-defined [16]. Some forms of symmetry have been exploited [17,44] and, in theory, general polynomial constraints on the 3-d points could be used. Most often, however, only planarity, parallelism, alignment and angles topology are used [18].

Amongst these constraint-based methods, computation differs between *multi-view* and *single view* methods. The former being usually modification of traditional 3-d modeling methodology [19], while the latter rely on the possibility of expressing geometric properties as linear constraints on the estimated quantities. For this reason, the 3-d directions, orthogonal or parallel to planes and edges of interest, should be estimated before the modeling (metric virtual reconstruction) itself [18,20,21]. These 3-d directions are called "dominant directions" [22] and form the *camera calibration matrix*.

In recent years, a remarkable attention is focused on 3-d reconstruction directly from a *single uncalibrated image*. It is well known that only one image itself cannot provide enough information for a complete and accurate 3-d modeling. However, some metric quantities can be inferred directly from a single image with the prior knowledge of geometrical scene constraints. Such constraints may be expressed in terms of vanishing points or vanishing lines, co-planarity, special interrelationship of features and camera constraints [23,24].

There are many studies on the problem of *single view* based calibration, pose and modeling in literature [25–27]. So, there are approaches on constraints-based *camera projection matrix recovery* (using geometric, space topology, photo-realistic and texturing cues) [5,18,20,28,29], as well as particular approaches on applying single view techniques for demolishing buildings modeling from a single historical photography [7,24,30–34]. Most of the studies are usually under the assumption of square (i.e. zero-skew and unit aspect ratio) or even rectangular (i.e. zero-skew and known aspect ratio) photography *dots*. However, these assumptions are not valid for historical photography with a distorted film digitization and development, and may not be applicable to old-fashion camera equipments or even to some off-the-shelf modern digital cameras with skew presence.

In particular: for *geometric cues* based modeling Wilczkowiak et al. [33] and Chen et al. [34] expand the idea to general parallelepiped structures, and use the constraints of parallelepipeds for camera calibration. Wilczkowiak et al. [21] also present a complete duality that exists between the *intrinsic* metric characteristics of a parallelepiped and the *intrinsic* parameters of a camera. Also, for a wide variety of man-made environment (architecture, façades, etc.), a *cuboid* is a reasonable model. Caprile and Torre [35] propose a method for camera calibration from vanishing points computed from the projected edges of the cuboids. These vanishing points correspond to three mutually orthogonal directions in space, which can provide three independent constraints to the *intrinsic* parameters of a camera.

For *line photogrammetry* based modeling several approaches that make use of vanishing points and vanishing lines have been proposed for either camera's calibration, or scene reconstruction. In this domain, the line features in the images are the observations. However, there is an explicit parameterisation for the edges in object space and this increase the complexity of the constraints' formulation as it is stated by Patias et al. [36], while Criminisi et al. [16] study the problem by computing 3-d affine measurement from a single perspective image. The above approaches are based on the vanishing line of a reference plane and the vanishing point in a vertical direction.

Some of the traditional approaches for solving the camera projection matrix recovery problem utilize particular *photo-realistic cues*, such as lighting, shading, texturing and defocusing [28,29]. But, this kind of cues are usually not present in historical photography, and even more these methods make strong assumptions on shape, reflectance or exposure and tend to require a controlled environment, which is often not available and an extra software vertical application is needed.

Zhang et al. [25] propose a method, which combines a sparse set of user-specified *space topology cues*, such as surface position, normals, silhouettes and creases, to generate a well-behaved 3-d surface satisfying these constraints.

Several approaches have been reported recently for the exploitation of the basic image geometry for damaged or destroyed buildings' modeling using single image techniques [7,19,24,30–32]. All these approaches are based on a square dot assumption (zero-skew). In particular, L. Grammatikopoulos et al. refer to three camera calibration approaches using single images of man-made objects [30]. These three techniques are based on vanishing points, image line parameters and image point observations, all of them with the assumption of square *dots* in photography (i.e. zero-skew single photography). Frank van den Heuvel [24] reports for an accurate virtual reconstruction of the demolished building called "Kommandantur", located at the historical center of Berlin. In this paper a single uncalibrated image from the Albrecht Meydenbauer archives captured in 1911 was used (http://www.geo.tudelft.nl/frs/architec/ Meydenbauer/). Also, in this study skew absence was assumed as well.

1.2. The proposed approach

Inspired by the ideas of new image-based modeling approaches [6,7], introduction of modern computing tools in CAAD [9,10], single view based camera calibration and pose recovery [23,24], reverse image-to-model CAD-based projection for sensor attitude estimation [15,37,45], building modeling [38,39], and references [40,44] for buildings' a priori geometric constraints, the proposed method is