MULTI-RESOLUTION VIRTUAL PLANE BASED 3D RECONSTRUCTION USING INERTIAL-VISUAL DATA FUSION

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Abstract: In this paper a novel 3D volumetric reconstruction method, based on the fusion of inertial and visual information and applying a quadtree-based compression algorithm, has been proposed. A network of cameras is used to observe the scene. Then beside of each camera, a fusion-based virtual camera is defined. The transformations among the cameras have been estimated. Then a set of horizontal virtual planes have been passed through the volumetric scenes. The intersections of these virtual planes and the object within the scene, or in other words the virtual registration layers, have been obtained by using the concept of homography. Then quadtree-based decomposition has been applied to the registration layers and consequently the obtained layers (2D) are stacked to produce the 3D reconstruction of the object. The proposed method has the ability of adjusting the compactness or the resolution of the result which can be defined with respect to the application or the storage resources, specially when the intention is to keep the sequence of 3D models in a dynamic scene.

1 INTRODUCTION

Building 3D volumetric models of the objects is one of the major research topics in the computer vision area. There have been many works in the area of 3D reconstruction. Khan in (Khan et al., 2007) proposed a homographic framework for the fusion of multi-view silhouettes. A marker-less 3D human motion capturing approach is introduced in (Michoud et al., 2007) using multiple views. Zhang in (Zhang et al., 2003) introduced an algorithm for 3D projective reconstruction based on infinite homography. Lai and Yilmaz in (Lai and Yilmaz, 2008) used images from uncalibrated cameras for performing projective reconstruction of buildings based on Shape From Silhouette (SFS) approach where buildings structure is used to compute vanishing points. Aliakbarpour and Dias in (Aliakbarpour and Dias, 2010a) proposed a method to SFS-based 3D reconstruction by fusion of inertial and visual information. 3D reconstruction of a dynamic scene is investigated in (Calbi et al., 2006) by Calibi. Franco in (Franco and Boyer, 2005) used a Bayesian occupancy grid to represent the silhouette cues of objects.

The use of IMU sensors to accompany compute vision applications is recently attracting attentions of the researchers. Dias in (Dias et al., 2002) investigated the cooperation between visual and inertial information. Lobo and Dias(Lobo and Dias, 2007) proposed an efficient method to estimate the relative pose of a camera and an IMU. Mirisola in (Mirisola and Dias, 2007) used a rotation-compensated imagery for the aim of trajectory by aiding inertial data. Fusion of image and inertial data is also investigated by Bleser (Bleser et al., 2006) for the sake of tracking in the mobile augmented reality. In our recent work(Aliakbarpour and Dias, 2010b), the problem of 3D reconstruction using inertial and visual information has been investigated. Tree-based data structures are appropriate to store spatial data. Most often they are used to partition a 2D space (quadtrees) or 3D space (octrees). An octree-based method to construct the 3D model of an object using SFS method is presented in (Kampel et al., 2002) by Kampel. An image registration approach based on reconstructed 3D octrees is proposed in (Ruwwe et al., 2008) by Ruwwe. Liu and Cooper in (Liu and Cooper, 2010) an approach to multi-view image-based 3D reconstruction

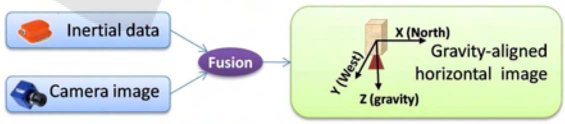

Figure 1: Fusion-based virtual camera.

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in which using octree to enhance the process speed is proposed. Moon et. al. in (Moon and Pan, 2010) proposed a human identification method for the intelligent video surveillance system by applying octree-based color quantization technique. A method to reduce 3D point clouds which are acquired by laser range finder is proposed in (Song et al., 2009) where octree is used to compress the data. Quadtree-based decomposition of image data is used in (Colleu et al., 2009) by Colleu et. al. for the sake of 3D video representation. Semi-automatically objects labeling using quadtree-based partitioning is proposed by Wu and Yang in (Wu and Yang, 2009).

This paper presents an approach for volumetric 3D reconstruction of an object within a scene. The scene is observed by a network of cameras. The cameras are coupled with an IMU. Fusion of inertial and visual information in each couple made it possible to consider a network of downward-looking virtual cameras whose images planes are horizontal. Moreover, a set of horizontal virtual planes which pass through the 3D space of the scene is considered, by using the inertial data. Then the intersection of each 3D world plane with the object volume has been obtained by using the concept of homography. In order to reduce the storage resource's usage and moreover enhance further processing speed(Liu and Cooper, 2010), a quadtree-based compression method has been applied. An algorithm has been introduced in order to perform the proposed compact 3D reconstruction method which produces a set of quadtree data structure as the result. This paper is organized as following: camera model is introduced in Sec. 2. An image registration method by fusion of inertial and visual information is proposed in Sec. 3. In Sec. 4 the compact 3D reconstruction algorithm by using quadtree method is described. Experimental results are demonstrated and discussed in Sec. 5 and eventually the conclusion is provided in Sec. 6.

2 CAMERA MODEL

In a pinhole camera model, a 3D point $\mathbf{X} = [\ X \quad Y \quad Z \quad 1\ ]^T$ in the scene and its corresponding projection $\mathbf{x} = [\ x \quad y \quad 1\ ]^T$ are related via the following equation (Hartley and Zisserman, 2003):

$$x = K\,[R|t]\,X \tag{1}$$

where K is the *camera calibration matrix*, R and t are rotation matrix and translation vector between world and camera coordinate systems, respectively. The camera matrix K, which is also called *intrinsic parameter matrix*, is defined by (Hartley and Zisserman, 2003):

$$K = \begin{bmatrix} f_x & 0 & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

in which f_x and f_y represent the focal length of the camera in the directions of x and y. The u_0 and v_0 are the elements of the principal point vector, p .

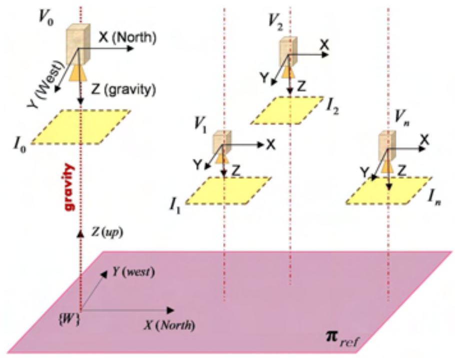


Figure 2: A network of virtual cameras: The coordinate frames of all virtual cameras are aligned to the world reference frame.

3 FUSION-BASED IMAGE REGISTRATION

The idea is to use a network of cameras to observe the scene. Each camera within the network is rigidly coupled with an IMU. Using fusion of inertial and visual information it becomes possible to consider a virtual camera instead of each couple. Such a virtual camera has a horizontal image plane and its optical axis is parallel to the gravity and is downward-looking. As a result, the image plane is aligned to the earth fixed reference frame. Fig. 2 shows a network of such virtual cameras. In order to obtain image plane of virtual camera, a homography-based approach described in (Aliakbarpour and Dias, 2010a) has been used which fuses inertial data from IMU and image plane of real camera to produce the corresponding virtual camera's image plane. As described in (Aliakbarpour and Dias, 2010a), the homography matrix which transforms the real camera image plane to its corresponding virtual camera image plane can be expressed as following:

$${}^{V}H_C = K\,{}^{V}R_C\,K^{-1} \tag{3}$$

where ${}^{V}R_C$ is the rotation matrix among the real and virtual cameras(Aliakbarpour and Dias, 2010a). The way of obtaining ${}^{V}R_C$ is explained in (Aliakbarpour and Dias, 2010a).

By taking the advantage of inertial data, a horizontal word plane π_{ref} , which is supposed to be common between all virtual cameras, has been defined in the world reference frame$\{W\}$ (see Fig. 2). As mentioned, the idea is to register virtual image data on the reference plane π_{ref} . The reference 3D plane π_{ref} is defined such a way that it spans the X and Y axis of $\{W\}$ and it has a normal parallel to the Z. In this proposed method the idea is to not using any real 3D plane inside the scene for estimating homography. Hence we assume there is no a real 3D plane available in the scene so our $\{W\}$ becomes a virtual reference frame and consequently π_{ref} is a horizontal virtual plane on the fly. Although $\{W\}$ is a virtual reference frame however it needs to be somehow defined and fixed in the 3D space. Therefore here we start to define $\{W\}$ and as a result π_{ref}. With no loss of generality we place O_W, the center of $\{W\}$, in the 3D space such a way that O_W has a height d w.r.t the first virtual camera, V_0. Again with no loss of generality we specify its orientation as same as the earth fixed reference. Then as a result we can describe the reference frame of a virtual camera $\{V\}$ w.r.t $\{W\}$ via the following homogeneous transformation matrix

$$^{W}T_V = \begin{bmatrix} ^{W}R_V & \mathbf{t} \\ \mathbf{0_{1\times3}} & 1 \end{bmatrix} \tag{4}$$

where $^{W}R_V$ is a rotation matrix defined as (see Fig. 2):

$$^{W}R_V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{5}$$

and $\mathbf{t}$ is a translation vector of the V 's center w.r.t $\{W\}$. Obviously using the preceding definitions and conventions, for the first virtual camera we have $\mathbf{t} = \begin{bmatrix} 0 & 0 & d \end{bmatrix}^T$.

After obtaining the virtual camera's image plane (from now on we call it *virtual image plane*) it is desired to find a homography matrix $^{\pi}H_V$ that transforms points from the virtual image plane I' to the common world 3D plane π_{ref} (recalling that these two planes are defined to be parallel). Here we continue to formally define such a homography matrix using the rotation and translation between these two planes (I' and π_{ref}). A 3D point $\mathbf{X} = \begin{bmatrix} X & Y & Z & 1 \end{bmatrix}^T$ lying on π_{ref} can be projected onto virtual image plane as

$$\mathbf{x} = {}^{\pi_{ref}}H_v \mathbf{X} \tag{6}$$

where $^{\pi_{ref}}H_v$ is a homography matrix which maps the π_{ref} to the virtual image plane and is defined by

$$^{\pi_{ref}}H_v = K\begin{bmatrix} \mathbf{r}1 & \mathbf{r}2 & t \end{bmatrix} \tag{7}$$

in which $\mathbf{r}1$, $\mathbf{r}2$ and $\mathbf{r}3$ are the columns of the 3×3 rotation matrix and t is the translation vector between the π_{ref} and camera center (Hartley and Zisserman, 2003). We recall that all virtual cameras have the same rotation w.r.t world reference frame $\{W\}$. In

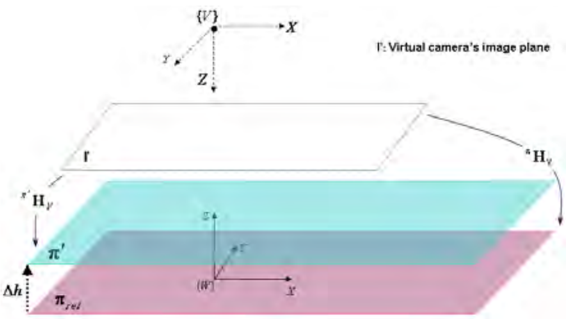


Figure 3: Extending homography for planes parallel to π_{ref}.

other words it can be thought there is no rotation among the virtual cameras. $^{W}R_V$ or the rotation matrix between a virtual camera and $\{W\}$ was described through Eq. (5). Considering $^{W}R_V$ from Eq. (5), π_{ref} as the interesting world plane and $\mathbf{t} = \begin{bmatrix} t_1 & t_2 & t_3 \end{bmatrix}^T$ as the translation vector (among I' and π_{ref}) and eventually K as camera calibration matrix (K is defined in Eq. 2), the Eq. (7) can be rewritten as :

$$^{\pi}H_V^{-1} = \begin{bmatrix} f_x & 0 & f_x t_1 + u_0 t_3 \\ 0 & -f_y & f_y t_2 + v_0 t_3 \\ 0 & 0 & t_3 \end{bmatrix} \tag{8}$$

In order to estimate $\mathbf{t}$ an approach described in (Aliakbarpour and Dias, 2010a) will be used.

The homography matrix from virtual image plane to the world 3D plane π_{ref} has been already obtained as $^{\pi}H_V$ (Eq. (8)). For the sake of multi-layer reconstruction, it is desired to also obtain the homography matrix from a virtual image to another world 3D plane parallel to π_{ref} once we already have $^{\pi}H_V$ (see Fig. 3). Lets consider π' as a 3D plane which is parallel to π_{ref} and has a height Δh w.r.t it. Then by substituting t_3 in the equation (8) with $t_3 + \Delta h$ and expressing it via $^{\pi}H_V$ (the available homography between the virtual camera image plane and π_{ref}) we have:

$$^{\pi'}H_V^{-1} = {}^{\pi}H_V + \Delta h \begin{bmatrix} \mathbf{0_{2\times2}} & P \\ 0 & 1 \end{bmatrix} \tag{9}$$

where $P = \begin{bmatrix} u_0 & v_0 \end{bmatrix}^T$ is the principal point of the virtual camera V.

4 COMPACT 3D RECONSTRUCTION

The method for registering image data onto a set of virtual horizontal planes based on the concept of homography was introduced in Sec. 3. Indeed in our case the homography transformation can be basically interpreted as shadow on each virtual horizontal 3D

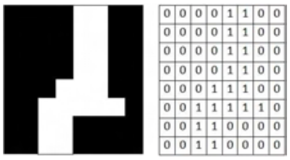


Figure 4: Quadtree decomposition: left) A binary image. right) The binary array corresponding to the (a).

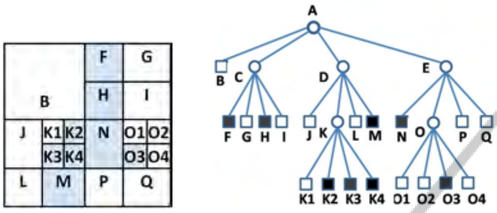


Figure 5: Quadtree decomposition: left) Quadtree-based block decomposition of the region. right) Quadtree representation of the decomposed blocks in (a).

plane created by a light source located at the camera position. Considering several cameras (remembering light sources) which are observing the object then different shadows will be created on the virtual horizontal 3D planes. Then the intersection between each of these planes and the observed object can be computed by using the intersections of all shadows. The result of the intersection is a plane and from now will be referred as the *registration* plane. Here, the idea is to use the concept of quadtree in order to keep or store the registration planes. The main advantage of using quadtree is to use less memory. Moreover it will increase the speed of further processing. We continue to briefly introduce the concept of quadtree-based image representation. Beforehand we assume to have a $2^n \times 2^n$ binary image. The quadtree-based image representation is based on the successive subdivision of the image into four equal-size quadrants (Samet, 1981). If the image does not consist entirely of 1's or entirely 0's, then it will be subdivided into four quadrants. Then for each quadrant we repeat the checking of the mentioned consistency until we get square blocks (might be even a single pixel) that contain homogeneous values (entirely 1's or entirely 0.s). Fig. 4-left shows a binary image as a sample. Its corresponding binary array can be seen in Fig. 4-right. Based on the described algorithm, the binary array is decomposed in blocks which is represented in Fig. 5-left. The quadtree form of the decomposition block is demonstrated in Fig. 5-right.

In order to perform the proposed 3D reconstruction method, an algorithm (Alg. 1) is provided which expresses the steps to do it. Here $\{camera\}$ and $\{virtual\,camera\}$ are respectively the sets of all cameras and virtual cameras , I indicates the image plane

Figure 6: Left: Cat statue, Middle: Couple of camera-IMU sensor, Right: A snapshot of the scene.

of a real camera, I' indicates the image plane of a virtual camera and I'' indicates a virtual 3D plane. The functions *height()* and *width()* get an image and return its height and width, respectively. The function *card()* is used to return the cardinality of the given set. The function ***Quadtree***$(R, blocks_{size})$ receives the R, as a registration plane and $blocks_{size}$ as the size of the blocks to be used for the decomposition (it can be thought as the compactness resolution). Eventually, the algorithm returns Q as a collection of compact 2D registration planes. The number of elements in this collection is $h_{max}+1$ and the the distance among the planes is Δh . Indeed Δh can be though as the horizontal resolution in the 3D reconstruction.

Algorithm 1: Multi-resolution virtual Plane based 3D reconstruction using inertial-visual data fusion. The resolution of the result depends to the $\triangle h$ and $blocks_{size}$ parameters. $\triangle h$ indicates the vertical distance (intervals) among the world virtual planes (see Fig. 3) and $blocks_{size}$ stands for the size of blocks to be used for quadtree-based decomposition.

for each v involved in $\{virtual\ camera\}$ **begin**
  obtain I'^{v} as the corresponding virtual image plane
end
Initialize Q as a collection of *quadtrees*
for $h = 0$ **to** h_{max} **step** Δh **begin**
  for each v involved in $\{virtual\,camera\}$ **begin**
    obtain projection I''^{v} from v to π^h
  end
  for each $i \in \{1..height(I''^{v})\}$ **begin**
    for each $j \in \{1..width(I''^{v})\}$ **begin**
      $n_c = card(\{virtual\,camera\})$ //cardinality
      $R(i,j) = \prod_{v=1}^{n_c} I''^{v}(i,j)$
    end
  end
  $Q(h)$=**Quadtree**$(R, blocks_{size})$
end
return Q // as volumetric 3D reconstruction of the object

5 EXPERIMENTS

Experimental results of the proposed method are described here. The idea is to perform the 3D reconstruction of a cat statue. Fig. 6 shows a cat statue, a couple of Camera-IMU and a snapshot of

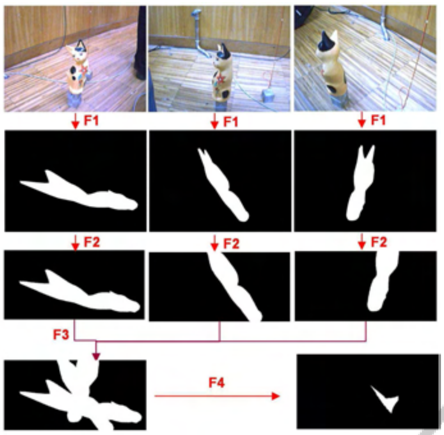


Figure 7: Steps to reach one 2D layer among 47 used layers for 3D reconstruction (in this example the layer height is 380*mm*). F1: Reproject black and white images to virtual camera image plane. (after background subtraction and binarization) F2: Reprojection of virtual image plane onto a 2D world virtual plane (registration plane) at a height=380*mm*. F3: Putting the three world virtual planes (merging). F4: Keeping just the intersected points.

the setup, from left to right respectively. The used camera is a simple FireWire Unibrain camera and a MTi-Xsens containing gyroscopes, accelerometers and magnetometers is used as the IMU. Firstly the intrinsic parameters of the camera camera is estimated using *Bouguet Camera Calibration Toolbox* (Bouguet,) and then *Camera Inertial Calibration Toolbox (Lobo and Dias, 2007)* is used for the sake of extrinsic calibration between the camera and IMU (to estimate$^{C}R_{IMU}$). The IMU-Camera couple is placed in some different positions. A simple and thin string is hanged near to the object. Two points of the string are marked. Then the relative heights between these two marked points and the first camera (indeed here the IMU-camera couple in the first position) are measured manually. The relative heights can also be measured using some appropriate devices such as altimeters. Note that these two points are not needed to necessarily be on a vertical line, but since we did not have altimeter available, then we used two points from a vertically hanged string in order to minimize the measuring error. Afterwards, in each position a pair of imagery-inertial data is grabbed. Fig. 7-top row shows three exemplary images taken from three different views. Then corresponding virtual images are obtained. Fig. 7, 2^{th} row shows the mentioned virtual image planes. Using the mentioned 2-points-heights method, which is described in (Aliakbarpour and Dias, 2010a), the translations between cameras in three position are estimated. By now we have the images from views of virtual cameras. The next step is to consider a set of registration planes (world

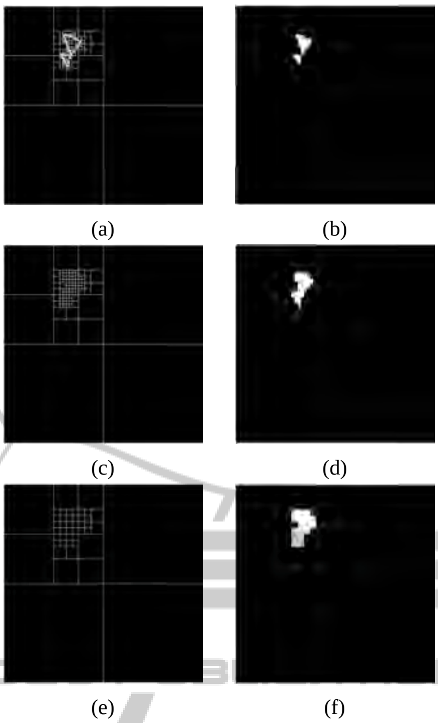
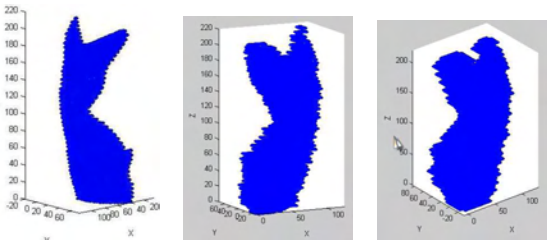


Figure 8: Lefts: quadtree-based decomposition blocks, corresponding to an exemplary results. Right: result images after applying the quadtree-based decomposition blocks. Block sizes (resolutions): 1, 8 and 16 pixels corresponding to the first, second and last raws, respectively.

virtual planes) and then reproject the three virtual camera images onto these registration planes. Here 47 registration planes are used. The height of lowest one is 480*mm* w.r.t first camera and the highest one is 250*mm*. The distance between the virtual 3D planes is considered as 5*mm*. As an example, the 3^{th} row of Fig. 7 indicates the reprojection of the three virtual camera images onto a registration plane with height=380*mm*. The merging of these views are shown in Fig. 7-bottom-left. Then the intersection of them is presented in Fig. 7-bottom-right (as the final registration plane, of course before compressing). After having such a registration virtual plane, the described quadtree algorithm has been applied on them. Fig. 8 demonstrate different levels (resolution) of quadtree-based decompositions applied on an exemplary registration plane. Its left column indicates some proposed decomposition blocks and the right column shows the related image after using such decomposition blocks (each row corresponds to a particular resolution). As can be seen in these images, for such a registration plane in which just a small part is occupied, it would be adequate to apply the quadtree compression method in order to store as less as possible memory for keeping the registration layer. It is



(a) (b) (c)

Figure 9: Results of quadtree virtual planes-based reconstruction. They are after assembling the quadtree-based decomposed registration layers (here, 47 layers). (a) maximum resolution (the decomposition block's size is 1). For (b) and (c) the size of the decomposition blocks are 8 and 16, respectively.

seen in this example, three quarters and two octants are completely empty and just two octants are partially occupied.

After repeating the operations for all 47 virtual registration planes and assembling them together, the result become the 3D reconstruction of the object. Fig. 9 demonstrates the result of the 3D reconstruction. Fig. 9-a is the result when the maximum resolution, or in other words blocks with the size equal to one, has been used for each registration layer. Fig. 9-b and Fig. 9-c are the results when the decomposition blocks with the size of 8 and 16 have been used, respectively. Depend to the application and the volume-size of the scene, the resolution for the decomposition blocks and moreover, the horizontal resolution (the distance between registration planes which is indicated as $\triangle h$ in the Algorithm 1), can be adjusted.

6 CONCLUSIONS

A multi-resolution 3D reconstruction using inertial-visual data fusion has been proposed in this paper. The proposed approach is based on obtaining the homography matrices among a set of virtual planes and the image plane. An algorithm has been introduced in order to perform the proposed 3D reconstruction method and produces a set of quadtree data structure. Depend to the application and the volume-size of the scene, the resolution for the decomposition blocks can be adjusted. Moreover for the same reason the vertical distance among the virtual registration layers can be increased or decreased in order to adjust the interesting resolution. Finally, experimental results demonstrate the efficacy of using the proposed method for the sake of 3D volumetric reconstruction.

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