Paper:

Voting-Based Approach to Nullspace Search for Correspondence Matching and Shape Recovery

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A simultaneous search, called *nullspace search*, for matching correspondences among images and recovering 3-D objects is proposed by using a voting-based method to circumvent erroneous recovery of 3-D objects arising from wrong matched correspondences among images. It is able to avoid occlusion problems and cope with remarkable changes in visibility in a long image sequence. An experiment is done with synthetic and real image sequences, consisted of 30 images of a sphere and 10 images of a toy house, under the condition that 3-D points are occluded at most 50% of the sequence and the camera moves with rotational as well as translational motions. The proposed method gives a basis for organizing multiple dynamic images where occlusion occurs frequently.

Keywords: correspondence matching, shape recovery, occlusion, voting

1. Introduction

The recovery of 3-D objects from a sequence of images usually involves two successive processes; the first is image matching for finding corresponding projections among images [1], and the second is 3-D position estimation of geometric features, which form 3-D objects, using the result of the first matching process (e.g., [2–6]). Most of the existing methods employ correlation matching [7] in the first process, which compares intensity values within small image regions for two successive images. However, if remarkable changes in visibility and occlusions occur, it fails to find the corresponding projections. Since these problems are likely to happen in a long sequence of images or multiple images, correlation matching is inadequate for the applications such as constructing 3-D dynamic virtual worlds from multiple cameras surrounding the 3-D objects [8].

In order to deal with remarkable changes in visibility and occlusions, a simultaneous search, called *nullspace search*, for matching correspondences among images and recovering 3-D objects is proposed by using a voting-based method. The nullspace search is mathematically equivalent to search the solutions for a set of simultaneous linear equations

$$\boldsymbol{A}_i\boldsymbol{x}_i = \boldsymbol{0}, \quad i = 1, \ldots, m,$$

where m and $\boldsymbol{A}_i$ are unknown. In general, voting repeatedly generates relevant model parameters from randomly sampled data as a series of hypotheses, and finally produces the solutions supported by a remarkable number of the hypotheses [9–11]. The proposed method first constructs a matrix $\boldsymbol{A}_j$ from randomly sampled projections, and then votes $\boldsymbol{x}_j$, which is obtained by solving $\boldsymbol{A}_j\boldsymbol{x}_j = \boldsymbol{0}$, into a parameter space. After sufficient iterations are completed, the vectors $\{\boldsymbol{x}_j\}$ having the votes cast larger than a predefined threshold are detected, and they are considered as geometric features of the 3-D objects. Thus, the proposed method can naturally combine multiple image data, and it successfully recovers 3-D objects by thresholding at the final step even if the randomly constructed matrices $\{\boldsymbol{A}_j\}$ contain wrong corresponding projections.

Section 2 reviews multiple view geometry of points, and then provides linear equations describing the perspective projection process. Section 3 formulates correspondence matching and shape recovery from a sequence of images using linear algebra. The formulation is called nullspace search. Section 4 presents a voting-based algorithm for nullspace search. Section 5 demonstrates the performance of our algorithm with synthetic and real image sequences.

2. Multiple View Geometry of Points

The relationship between 3-D points and their perspective projections onto images is reviewed. The multiple

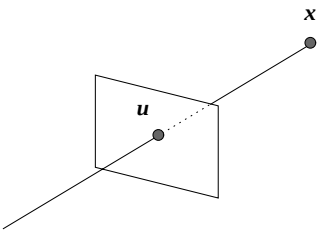


Fig. 1. Perspective projection of a point.

view geometry derives linear equations for the relationship. The expressions derived in this section are used in formulating correspondence matching and shape recovery in Section 3.

Let $\boldsymbol{x} = (X, Y, Z, 1)^\top$ be a 3-D point and $\boldsymbol{u} = (x, y, 1)^\top$ be a perspective projection of $\boldsymbol{x}$ onto an image in homogeneous coordinates (**Fig.1**). The relationship between a 3-D point $\boldsymbol{x}$ and its perspective projection $\boldsymbol{u}$ is written as

$$\lambda \boldsymbol{u} = \boldsymbol{P}\boldsymbol{x} \quad \ldots \quad (1)$$

where λ is an arbitrary nonzero scalar and $\boldsymbol{P}$ is a 3×4 matrix called a perspective projection matrix [12], which models the perspective projection process in homogeneous coordinates. By eliminating a scale factor λ in Eq.(1), a homogeneous system of linear equations in $\boldsymbol{x}$

$$\boldsymbol{A}\boldsymbol{x} = \boldsymbol{0}, \quad \boldsymbol{A} \equiv \begin{bmatrix} (x\boldsymbol{p}_3 - \boldsymbol{p}_1)^\top \\ (y\boldsymbol{p}_3 - \boldsymbol{p}_2)^\top \end{bmatrix} \in \mathbb{R}^{2\times 4} \quad \ldots \quad (2)$$

is obtained, where $\boldsymbol{p}_i^\top$ is the ith row of the matrix $\boldsymbol{P}$. If at least two projections of a 3-D point are observed, a system of equations in $\boldsymbol{x}$ can be uniquely solved except for degenerate cases.

3. Problem Formulation for Image Matching and Recovering

The two problems of matching correspondences and recovering 3-D shape are formulated. In this formulation, the two problems are equivalent to search the basic vectors spanning the nullspaces that represent 3-D points.

3.1. Shape Recovery

Suppose that a 3-D object is composed of m points $\boldsymbol{x}_i$, $i = 1, \ldots, m$, and it is observed from n cameras. Let $\boldsymbol{A}_{ij}$ denote a 2×4 matrix for the jth projection on the ith image in Eq.(2). For the ith 3-D point $\boldsymbol{x}_i$, the collection of the projections provides an overdetermined homogeneous system of linear equations

$$\boldsymbol{A}_i\boldsymbol{x}_i = \boldsymbol{0}, \quad \boldsymbol{A}_i^\top \equiv [\boldsymbol{A}_{i1}^\top \, \boldsymbol{A}_{i2}^\top \, \ldots \, \boldsymbol{A}_{in_i}^\top] \quad \ldots \quad (3)$$

where n_i is the number of the projections for $\boldsymbol{x}_i$. Note that the number n_i may be different from another point $\boldsymbol{x}_j, i \neq j$.

The solution to Eq.(3) provides the position of the 3-D point $\boldsymbol{x}_i$ in homogeneous coordinates. To avoid the trivial solution $\boldsymbol{x}_i = \boldsymbol{0}$, the coefficient matrix $\boldsymbol{A}_i$ is rank-deficient, i.e., the rank of $\boldsymbol{A}_i$ is at most 3. This condition implies that the solution $\boldsymbol{x}_i$ is in the nullspace of the coefficient matrix $\boldsymbol{A}_i$, i,e.,

$$\boldsymbol{x}_i \in \mathcal{N}(\boldsymbol{A}_i) \quad \ldots \quad (4)$$

where $\mathcal{N}(\boldsymbol{A}) = \{\boldsymbol{x} \,|\, \boldsymbol{A}\boldsymbol{x} = \boldsymbol{0}\}$. The estimation of 3-D positions is, therefore, formulated as follows.

Problem 1 *Setting $\boldsymbol{A}_i$ to be a $2n_i \times 4$ matrix such that $2n_i \geq 4$, solve overdetermined homogeneous systems of linear equations*

$$\boldsymbol{A}_i\boldsymbol{x}_i = \boldsymbol{0}, \quad i = 1, \ldots, m.$$

This problem is solved by searching the solution $\boldsymbol{x}_i$ in the nullspace of the matrix $\boldsymbol{A}_i$. Since the vector spanning the nullspace is defined up to a scale factor, the normalization of the length of the vector is required, i.e., $||\boldsymbol{x}_i|| = 1$. From this normalization, the vectors to be estimated are distributed on the 3-dimensional unit sphere.

3.2. Correspondence Matching

If corresponding points among the images are not determined, the coefficient matrix $\boldsymbol{A}_i$ is unknown. Available data is the collection of the submatrix $\boldsymbol{A}_{ij}, i = 1, \ldots, m, j = 1, \ldots, n_i$. The construction of $\boldsymbol{A}_i$ in Eq.(3) is equivalent to correspondence matching among the images. Since the rank of $\boldsymbol{A}_i$ is at most 3 except for some degenerate configurations, each solution is in an 1-dimensional nullspace [13], and then

$$\dim \mathcal{N}(\boldsymbol{A}_i) = 1. \quad \ldots \quad (5)$$

This property of $\boldsymbol{A}_i$ leads to the following problem for correspondence matching.

Problem 2 *Let $\boldsymbol{A}_{ij}$ be a 2×4 matrix. From given data set $\boldsymbol{A}_{ij}, i = 1, \ldots, m, j = 1, \ldots, n_i$, find $2n_i \times 4$ matrices $\boldsymbol{A}_i$ such that*

$$\boldsymbol{A}_i^\top = [\boldsymbol{A}_{i1}^\top \, \boldsymbol{A}_{i2}^\top \, \ldots \, \boldsymbol{A}_{in_i}^\top] \quad \text{s.t. } \dim \mathcal{N}(\boldsymbol{A}_i) = 1.$$

4. Nullspace Search by Voting Method

A simultaneous search, called *nullspace search*, for solving Problem 1 and Problem 2 in the section 3 is proposed by using a voting-based method.

4.1. Characterizing the Problems

Problem 1 is an inverse problem, since it is solved by fitting a model to given data points. This problem is solved by a least-squares method, and then its solution is uniquely obtained. Problem 2 is also an inverse problem but different from Problem 1. The difference between Problems 1 and 2 is that the solution of Problem 2 is not uniquely determined. There are many combinations of the

submatrices $\{\boldsymbol{A}_{ij}\}$ for construction of the matrices $\{\boldsymbol{A}_i\}$ in Problem 2.

As mentioned in the previous section, the nullspaces to be estimated are distributed on the 3-dimensional unit sphere. To search the nullspaces, the proposed voting-based method repeatedly generates a hypothesis onto the 3-dimensional unit sphere, and finally the solutions are accepted by selecting the hypotheses supported by a large number of given data. This hypothesis generation is based on the following proposition.

Proposition 1 *Let $\boldsymbol{A}$ be a $M \times N$ matrix with $M > N$ and $\boldsymbol{B}$ be any $N \times N$ matrix which is obtained by selecting N rows from $\boldsymbol{A}$. If* $\mathrm{rank}(\boldsymbol{A}) = N - 1$, *then*

$$\mathrm{rank}(\boldsymbol{B}) = N - 1 \quad \ldots\ldots\ldots\ldots \quad (6)$$

or equivalently

$$\dim(\mathscr{N}(\boldsymbol{B})) = 1 \quad \ldots\ldots\ldots\ldots \quad (7)$$

and the matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ share an 1-dimensional nullspace.

Proposition 1 enables us to generate a hypothesis onto a nullspace on the 3-dimensional unit sphere from sampled data points as follows:

1. Randomly construct a 4×4 matrix $\boldsymbol{B}$ from given data.

2. If $\boldsymbol{B}$ has an 1-dimensional nullspace, vote 1 to the nullspace of $\boldsymbol{B}$.

If this hypothesis generation is iterated until an appropriate number, the nullspaces are estimated by detecting peaks of the votes on the $(N-1)$-dimensional unit sphere. Thus the estimation of 3-D point positions can be solved by this iteration.

4.2. Algorithm

In the above hypothesis generation, the computation of the nullspaces of given matrices is required. In our implementation, the singular value decomposition (SVD) is employed. If matrix $\boldsymbol{A}$ has only a zero singular value, then the nullspace of $\boldsymbol{A}$ is spanned by the right singular vector associated with the zero singular value. Therefore, setting $\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_N$ to be the singular values of the sampled $N \times N$ matrix $\boldsymbol{B}$ and $\boldsymbol{v}_1, \ldots, \boldsymbol{v}_N$ to be the corresponding right singular vectors, if the relationship $\sigma_1 \geq \sigma_2 \geq \cdots > \sigma_N = 0$ holds, the nullspace to be generated is the vector $\boldsymbol{v}_N$.

These properties of matrices lead to the nullspace search by using the voting-based method for correspondence matching and 3-D shape recovery.

Algorithm: Nullspace Search by Voting

Step 1: Repeat Step 2 to Step 6 until a predefined number.

Step 2: Randomly select two 2×4 submatrices $\boldsymbol{A}_{i_1 j_1}$, $\boldsymbol{A}_{i_2 j_2}$ from given data set $\{\boldsymbol{A}_{ij}\}$.

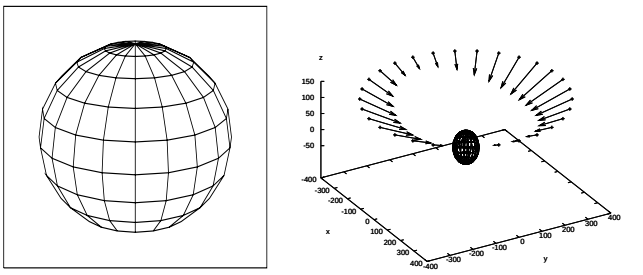
Step 3: Construct a 4×4 matrix $\boldsymbol{B}$ such that $\boldsymbol{B}^\top = [\boldsymbol{A}_{i_1 j_1}^\top \; \boldsymbol{A}_{i_2 j_2}^\top]$.

Step 4: Compute the SVD of $\boldsymbol{B}$ and let $\sigma_1 \geq \cdots \geq \sigma_4$ be its singular values and $\boldsymbol{v}_1, \ldots, \boldsymbol{v}_4$ be the corresponding right singular vectors in the unit length.

Step 5: If the smallest singular value is not equal to 0, i.e., $\sigma_1 \geq \cdots \geq \sigma_4 > 0$, then go to Step 2.

Step 6: Add 1 to the accumulator of the right singular vector $\boldsymbol{v}_4$ associated with the smallest singular value σ_4.

Step 7: Detect the vectors whose values of the accumulators are larger than a predefined constant.



(a) (b)

Fig. 2. (a) An example image of the spherical object. (b) 3-D configuration between the spherical object and the cameras.

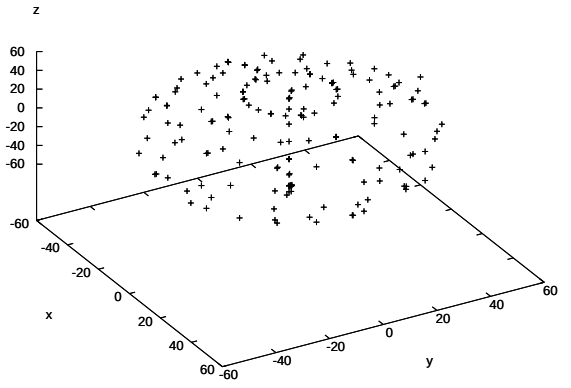
Vector $\boldsymbol{v}_4$ at Step 6 is a hypothesis that may or may not be a 3D point (in homogeneous coordinates) in the scene. If a $\boldsymbol{v}_4$ exists in the scene and is taken from several cameras, the $\boldsymbol{v}_4$ is repeatedly generated during the process from Step 2 and Step 6. As a result, the $\boldsymbol{v}_4$ receives a large number of votes after the process. Then a collection of 3D points $\{\boldsymbol{v}_4\}$ is recovered by thresholding at Step 7, i.e., Problem 1 is solved.

On the other hand, this algorithm does not seem to explicitly solve Problem 2. This is because the algorithm does not maintain the relations among corresponding points, i.e., $\boldsymbol{A}_{i1} \leftrightarrow \boldsymbol{A}_{i2} \leftrightarrow \cdots \leftrightarrow \boldsymbol{A}_{in_i}$, during the process. Instead, pieces of information about the correspondence relations obtained from random search at Step 2 through Step 5 are combined in the 3D space (in homogeneous coordinates) at Step 6. As a result, Problem 2 is implicitly solved. If $\boldsymbol{A}_i$ in Problem 2 is required, it is easily resolved by adding a procedure for maintaining the correspondence relations in memory into the algorithm.

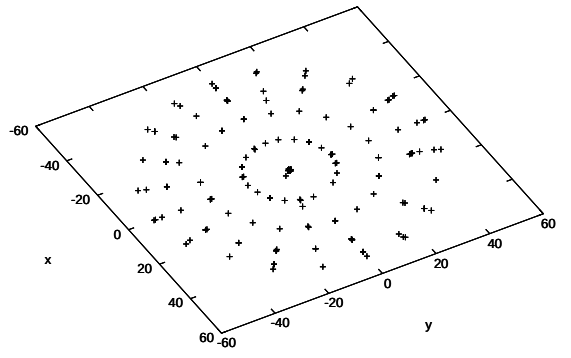
5. Experiments on Synthetic and Real Objects

The performance of the proposed algorithm is evaluated using a synthetic spherical object, shown in **Fig.2(a)**, and a real object "Model House", shown in **Fig.4**.

Fig. 4. The image sequence "Model House".



(a)



(b)

Fig. 3. (a) An oblique and (b) top views of the recovered 3-D points.

5.1. Synthetic Data

The spherical object is composed of 182 points which lie on the surface, as shown in **Fig.2(a)**. The images are taken with 30 cameras whose positions are placed in such a way as to surround it uniformly, shown in **Fig.2(b)**. In this figure, each point is placed at the center of a camera and the attached arrow stands for the direction of the camera. This arrangement of the cameras is common for application domains such as whole shape measurement and virtual world construction. Each image is digitized in 256×256 pixels, and the digitized coordinates of the image points are given to the algorithm. **Figs.3(a)** and **(b)** are oblique and top views of the recovered 3-D points, respectively.

The number of iterations in the voting process (Step 2 to Step 6) is set to be 10^6 times and the threshold for detecting peaks in the parameter space (Step 7) is set to be 10 in number. The two parameters of the algorithm are empirically determined. In general, it is impossible to optimally determine the parameters in advance, because information about 3-D objects to be recovered is required. The parameters used in this experiment, however, give good results for other synthetic image sequences, which fact is confirmed by trial and error. In this setting, the algorithm recovers the 181 points – the bottom point on the sphere is invisible in all the images – around 1 minute with the UltraSPARC-II 297MHz processor.

The 30 images of the spherical object have the occlusion problem; the 3-D points on the sphere are occluded in at most half of the 30 images. Furthermore, since the spherical object produces a similar repeated pattern over the image sequence such as **Fig.2(a)**, matching based on only image characteristics probably fail to detect the corresponding points over the images. The proposed method prevents the wrong detection from occurring by using the majority decision in the voting-based algorithm.

5.2. Real Data

The 10 images in **Fig.4** is created at Visual Geometry Group, University of Oxford. Each image is digitized in 768×576 pixels. In the experiment, feature points on the images are detected using the SUSAN corner detector [14], and only the points detected on the house are given to the algorithm. **Fig.6(a)** shows the recovered 3-D points by the algorithm. In **Fig.6(b)**, the wireframe model of the house is superimposed on the result in **Fig.6(a)** to clearly show the relation between the recovered points and the house.

The number of iterations in the voting process is set to be 10^7 times and the threshold for detecting peaks in the parameter space is set to be 55 in number. The two parameters of the algorithm are also empirically determined.

In the 10 images of the house object, occlusions and changes in visibility occur. As an example of occlusions, the right side of the house on the first image is not in view

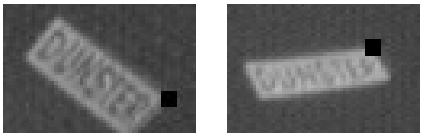


Fig. 5. The subimages around the right plates on the roof of the first (left) and last (right) images in the "Model House" sequence.

on the last image. This relatively large occluded region to the overall image plane leads to the significant error of the recovered objects, because most of the existing stereo methods assume that occluded regions are small relative to the overall image plane. The result in **Fig.6** shows that the proposed algorithm is not affected by the occluded region. As an example of changes in visibility, the front face of the house gives different views over the image sequence, in which the changes arise from rotational as well as translational camera motions, as shown in **Fig.5**. For the upper right corner points (black dots) in **Fig.5**, the normalized correlation between the 5×5 windows, encoded by vectors in $\mathbb{R}^{25}$, centered at the two points is -0.285 in value, i.e., the angle between the two normalized vectors in $\mathbb{R}^{25}$ is about $107°$, which is not an acceptable value for correlation-based matchers because they implicitly assume that the observed surface is parallel to the image planes. The proposed algorithm does not require the assumption. As a result the corner points on the front face are recovered, which is shown in **Fig.6**. This property gives the proposed algorithm the advantage of coping with changes in visibility over correlation-based matching methods.

6. Conclusions

In order to solve the two problems of correspondence matching and 3-D shape recovery from a sequence of images, the nullspace search is proposed by introducing a voting-based method. The method repeatedly generates relevant geometric parameters from randomly sampled projections as a series of hypotheses, and finally produces the geometric parameters, which represent 3-D objects, supported by a large number of the hypotheses. Thus, the method infers 3-D information by collecting evidence from a piece of insufficient 2-D information. This characteristic is the emphasis of the proposed method. Also it can, in principle, solve a wide variety of grouping and model fitting problems, in which a type of the model to be fitted is given but the number of the models is unknown.

In the experiment, two image sequences, 30 images of a synthetic spherical object, and 10 images of a real toy house are tested. Each image sequence is taken from perspective views in such a way as to surround the 3-D object. These camera positions are common for application domains such as 3-D virtual world construction. For the spherical object, the 3-D points are occluded at most

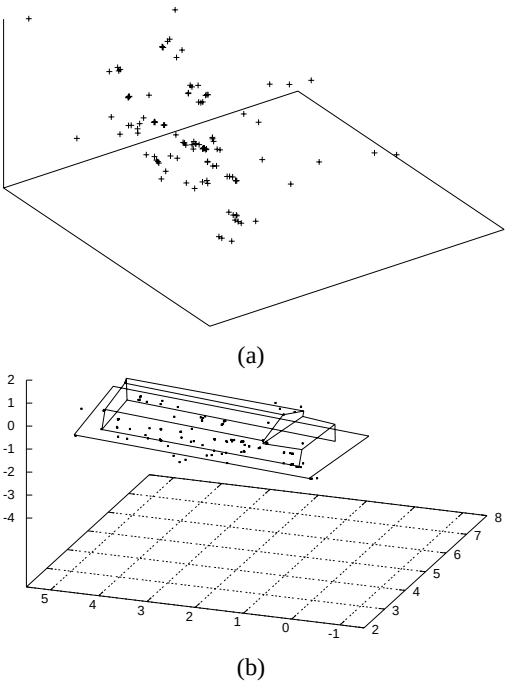


Fig. 6. (a) The result for the image sequence "Model House". (b) The wireframe model superimposed on the result.

50% of the 30 images, and for the house object, remarkable changes in visibility as well as occlusions happen due to rotational and translational motions of the camera. For such image sequences, matching based on only image characteristics such as correlation may fail to detect the corresponding points over the image sequence. The experiment indicates that the proposed method is not affected by occlusions and changes in visibility. On the other hand, the problem of determining the paremeters used in the algorithm – the number of iterations and the threshold for detecting peaks in the parameter space –, remains. For optimal or suboptimal determination of the parameters, an adaptive method that sequentially analyzes the distribution of vote scores in the parameter space may be useful. This topics of research will be discussed in the future.

Although voting requires a large number of iterations, the computational cost is overcoming due to current computer power. Also, due to the independence of computation at each trial in voting, parallel or cluster computers are suitable for its implementation. These aspects enable us to give a basic technique for capturing complicated and dynamic 3-D scenes from a sequence of images, which is of growing interest in the areas of computer vision and virtual reality.

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