Estimating the Next Sensor Position based on Surface Characteristics

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Abstract

In order to reconstruct the viewable surface of an object completely, multiple views of the same object have to be used and integrated into a common coordinate system. One of the major problems of the 3d surface reconstruction using a turntable, is the varying resolution in the direction to the camera, due to the varying distance of object points to the rotational axis of the turntable. To guarantee a uniform object resolution, we calculate the next angle dynamically, depending on the entropy of the surface part actually acquired. To minimize the loss of information and to guarantee a uniform surface resolution, we derive a relation between the entropy and the next viewing angle, based on the profile sections acquired in the last two steps of the acquisition.

1. Introduction

The reconstruction of the viewable object surface requires images from multiple views. The number of acquisition steps and the respective orientation of the camera relative to the object surface are unknown for arbitrary objects [3, 10]. Therefore, we need techniques, which estimate the next sensor position based on the measurement of the shape information captured in previous steps of the acquisition process and therefore generating a relationship between the sensor and the object of interest [9].

In this paper, we present a next-view-planning technique which estimates the next sensor position depending on the object's surface structure. The system relies only on the data acquired, where the position of the first acquisition step is arbitrary. Then, the next positions are estimated based on the profile section acquired in the previous step of the process. Figure 1 gives an overview of the iterative process for 3d surface reconstruction in static environments. Following an initial image acquisition, prominent features such as surface and shape characteristics are extracted and used for a subsequent registration of the actual view with the 3d-data acquired so far. Next, the newly acquired data is used to decide where the next sensor position should be in order to scan the surface optimally. Depending on the already performed acquisition steps, a decision is made whether it is necessary to make further acquisition steps or not.

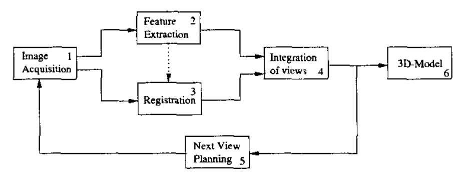

Figure 1. Iterative procedure for 3d surface reconstruction.

The paper is organized as follows. Section 2 describes the equipment used. Section 3 describes the strategy for estimating the next sensor position based on the surface structure and Section 4 presents experimental results showing the balance between surface resolution and amount of data. Finally, in Section 5 conclusions are drawn and future work is outlined.

2. Acquisition System

The acquisition method used for estimating the 3d-shape of objects is shape from structured light, based on active triangulation [1]. The camera is positioned between the two lasers facing the measurement area. Figure 4 depicts the complete hardware setup (a) and its geometry (b). The complete system consists of:

- 1 Turntable with a diameter of 50 cm, which can be rotated about the Z-axis, used to move the object of interest through the acquisition area.
- 1 CCD-Camera (b/w) with a 16mm focal length, a resolution of 768x572 pixels, and a distance of 40 cm to

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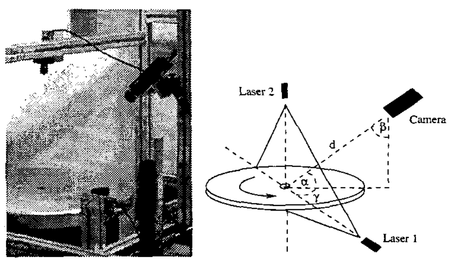


(a) Equipment (b) Arrangement

Figure 2. Acquisition system.

the rotation center. The angle between the optical axis and the rotation plane is approx. 45 degrees.

- 2 red lasers to illuminate the scene, one mounted on the top (distance to rotation plane=45 cm), one beside the turntable (distance to rotation center=48 cm). Both lasers are extended with cylindrical lenses to spread the laser beam into one illuminating plane. The laser light plane intersects with the object surface, forming one laser stripe. The reason to use two lasers instead of one is the occurance of occlusions during acquisition [8].
- 1 Intel Pentium PC under Linux operating system.

3. Sensor Planning

The problem of 3d-acquisition using a turntable is the varying resolution in direction to the camera due to the varying rotation of object points in respect to the rotational axis of the turntable [5]. Therefore, we use a next view planning technique [3] that ensures a uniform object surface resolution and makes it possible to sense high-structured parts of the object in higher resolution than parts with uniform structure.

The problem solutions on estimating the next best view (NBV) can be divided into three categories:

- Minimization of occlusions: Occlusions are interpreted as filled polygons. Then, a set of sensor positions and angles relative to the surface of the object are computed for each pixel of this polygons. The result of this step is a set of intervals from which the polygon pixel is visible. Decomposing these intervals gives the next sensor position. Whereas [3, 2] analyses range images, [6] uses volume models, to solve the NBV-Problem.
- Analyzing the geometric properties of the surface: In [4] the surface structure is given by triangulated surface points. The surface is completed by stepwise refinement. Regions, which show highly structured parts are scanned with higher density than regions which show low structured parts.
- Heuristic search and objective functions: The set of next sensor positions is reduced by applying a heuristic search. The best position is estimated by maximizing an objective function [7, 11].

The result of the first category approaches is information about the position and orientation of occlusions in the scene. This information is two or three dimensional. To reduce occlusions, a system, which allows a movement of more than one degree of freedom, is needed. The turntable allows a movement about the z-axis and the next best sensor position will be estimated by the analysis of the surface structure. The notion of the next "best" sensor position can be defined in two ways:

- The system should achieve a minimal number of acquisition positions and steps to reconstruct the object of interest.
- Computing those acquisition positions and directions, which gives the best reconstruction results.

In this work, we develop a system, which achieves a minimal number of acquisition steps by accomplishing given accuracy requirements.

3.1. Adaptive Image Acquisition

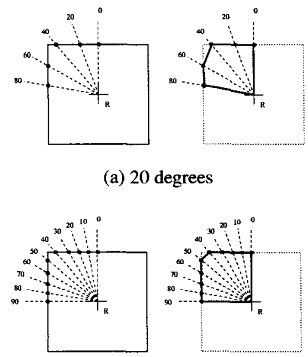
One problem of 3d surface reconstruction using a turntable, is the varying resolution in the direction to the camera, due to the varying distance of object points to the rotational axis of the turntable. The varying resolution leads to a loss of surface features. Figure 3 shows two examples to the loss of information. Sampling the object with a constant angle of 20 degrees (Figure 3a) we loose one corner of the square. On the other side, sampling the object with a lower constant angle, the loss of information is less (Figure 3b) than sampling with a higher constant angle. Therefore, the accuracy of reconstructions can be improved by decreasing the sampling angle, whereas the effort of the acquisition process will be increased.

3.2. Complexity

The maximum number of acquisition steps depends on the camera resolution. Therefore the minimum angle is given by

$$\phi_{min} = \arctan \frac{r}{A}, \qquad (1)$$

where r is the distance of one surface point to its center of revolution and A is the resolution of the camera. The



(a) 20 degrees

(b) 10 degrees

Figure 3. Sampling with equiangular steps.

maximum number of acquisition steps is then given by

$$N_{max} = \frac{360}{\phi_{min}}. \qquad (2)$$

Let n be the desired number of maximal acquisition steps. The complexity of the NBV-problem is then given by

$$C_{NBV} = \sum_{i=1}^{n} \binom{N_{max}}{i}, \qquad (3)$$

viewed as the more general set theory problem of finding a minimal number of subsets that completely covers a set [10], which is in the class of NP complete problems and therefore only solvable with polynomial effort.

The limitation to a directed movement and the definition of a maximum angle ϕ_{max} reduces the complexity, because the number of possible next positions will be decreased.

3.3. Computing the Next Sensor Position

To estimate the next sensor position, we have to calculate the distance of the acquired surface points relative to the axis of rotation. The calculation of the next rotational angle is given by the following expressions:

- Defining and calculating a distance function: Let L be a set of back transformed surface points P given by one acquisition step. For each of this points, we calculate the Euclidean distance d_{norm} to the axis of rotation $R_{axis} = R + v \cdot S$. d_{norm} given by

$$d_{norm} = \frac{|S \times (P - R)|}{|S|}. \qquad (4)$$

- Defining and calculating the gradient of one surface point: Be $P_{i,max}$ the surface point with the maximum Euclidean distance d_{norm} to R_{axis} in the i-th acquisition step. The gradient g_i is calculated by the following algorithm:
  1. Estimation of $d_{i,max}$: This is explicitely given by $P_{i,max}$.
  2. Estimation of the surface point P_{i-1} with the same z-component as $P_{i,max}$ and calculation of $d_{i-1}(P_{i-1})$.
  3. Computation of the approximated gradient g_a between d_{i-1} and $d_{i,max}$.
  4. Computation of the gradients angle α_a of g_a.
  5. Estimation of the surface point P_i with the same z-component as the point $P_{i-1,max}$ and calculation of $d_i(P_i)$.
  6. Computation of the approximated gradient g_b between $d_{i-1,max}$ and d_i.
  7. Computation of the gradients angle α_b of g_b.
  8. Estimation of the region with the highest entropy. This region is denoted by $max(\alpha_a, \alpha_b)$.

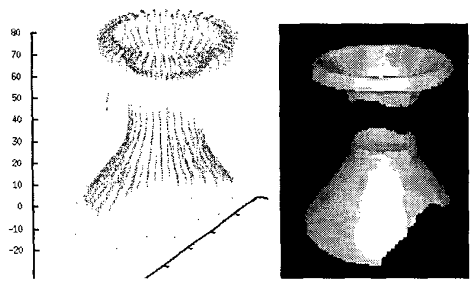
- Calculation of the next rotation angle: The gradient value could be positive, negative or zero, depending on an increasing, decreasing, or unchanging entropy. Table 1 shows the calculation of the relative change $\phi_{i,rel}$ and the absolute angle $\phi_{i,abs}$ depending on the sign of the gradient g_i, the gradient angle α_i and the relative change $\phi_{i-1,rel}$ of the $(i-1)$-th step, where the threshold t_α encodes the geometric conditions under which the system sampling density will be increased.

g_i	α_i	$\phi_{i-1,rel}$	$\phi_{i,rel}$	$\phi_{i,abs}$
>0	$>t_\alpha$	$>\phi_{min}\cdot 2$	$\frac{\phi(P_i)-\phi(P_{i-1})}{2}$	$\phi_{i-1}-\phi_{i,rel}$
		$<\phi_{min}\cdot 2$	ϕ_{min}	$\phi_{i-1}-\phi_{i,rel}$
		$=\phi_{min}$	ϕ_{min}	$\phi_{i-1}+\phi_{i,rel}$
>0	$\leq t_\alpha$	$-$	$\phi_{i-1,rel}$	$\phi_{i-1}+\phi_{i,rel}$
<0	$>t_\alpha$	$>\phi_{min}\cdot 2$	$\frac{\phi(P_i)-\phi(P_{i-1})}{2}$	$\phi_{i-1}-\phi_{i,rel}$
		$<\phi_{min}\cdot 2$	ϕ_{min}	$\phi_{i-1}-\phi_{i,rel}$
		$=\phi_{min}\cdot 2$	ϕ_{min}	$\phi_{i-1}+\phi_{i,rel}$
<0	$\leq t_\alpha$	$<\phi_{max}/2$	$\phi_{i-1,rel}\cdot 2$	$\phi_{i-1}+\phi_{i,rel}$
		$\geq\phi_{max}/2$	ϕ_{max}	$\phi_{i-1}+\phi_{i,rel}$
$=0$	$=0$	$<\phi_{max}/2$	$\phi_{i-1,rel}\cdot 2$	$\phi_{i-1}+\phi_{i,rel}$
		$\geq\phi_{max}/2$	ϕ_{max}	$\phi_{i-1}+\phi_{i,rel}$

Table 1. Next rotation angle.

4. Results

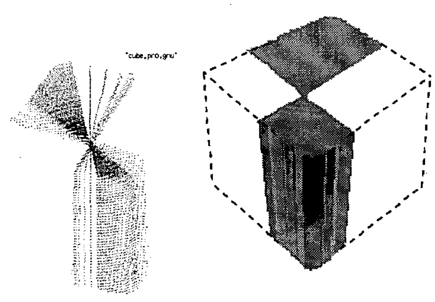
Figure 4 shows the reconstruction of an archaeological amphore. The symmetry axis of the pottery and the rota-



(a) reconstr. (b) rendered

Figure 4. Reconstruction of pottery.

tional axis of the turntable are roughly justified. The minimum angle was defined as $\phi_{min} = 4deg$ and the maximum angle as $\phi_{max} = 12deg$. Analyzing the reconstructed data shows a displacement of 1.8 mm in x-direction and 2.1 mm in y-direction. Therefore, the object was sampled with varying relative angles in 36 steps.



(a) reconstr. (b) rendered

Figure 5. Partial reconstruction of a cube.

The next object of interest is a cube with a side length of 3 cm. Figure 5 shows the partial reconstruction using an absolute angle of 90 degrees. The minimum angle was defined with $\phi_{min} = 1deg$, the maximum angle as $\phi_{max} = 8deg$. Because of the higher entropy of this region, we see a higher sampling density at the corner of the cube. The acquisition needs 50 steps. Table 2 shows the balance between sampling with equiangular and adaptive steps:

Sampling	Steps	Percent of 90
1 degree equiangular	90	100
8 degree equiangular	11	12
NVP - adaptive	50	55

Table 2. Cube sampling.

5. Conclusion

We have presented a next-view-planning technique to reduce the computational effort in 3d surface reconstruction using a turntable up to 50% without decreasing the quality of reconstruction. The surface structure is preserved since high structured parts of the surface are sampled with higher density than unstructured parts. Future work will be directed towards increasing the DoF of the acquisition system in the z-direction to minimize camera occlusions.

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