Correspondence Assignment using Phase-Shifting Fringe or Band-Limited Pattern Projection

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In our contribution, we compare the correspondence assignment qualitiy for two different structured light approaches in conjuction with stereophotogrammetry. As a reference system the phase-shifting fringe projection method is used and compared to the approach using band-limited statistical patterns. It is shown, that both evaluation schemes share certain similarities and that the resulting correspondence assignment has a comparable accuracy.

1 Introduction

In the last years, the interest in developing 3D sensors capable of delivering dense and accurate shape information at a real time rate has grown tremendously. Although single-shot solutions seem to be the most straightfoward approach to deal with this task, it is usually not possible to acquire dense and accurate depth information at the same time. On the other hand, temporal coding concepts are capable of delivering dense and accurate depth information, but as an image sequence is needed, it is technically more challenging to realize a real time system. Nevertheless, several proposals for highspeed temporal coding schemes have been presented in the last years, which can be mainly categorized in adapted phase-shifting regimes [1, 2, 3] and statistical pattern projection approaches [4, 5, 6]. Therefore, we want to compare the correspondence assignment quality when using the well-known phase-shifting fringe projection method or when using the statistical pattern projection method.

2 Structured Illumination Concepts (PSF)

The role of structured illumination in stereophotogrammtery is to superimpose visiual features (spatial or temporal) onto the object under test. A structured illumination method consists of two essential parts. The illumination sequence design and the evaluation strategy imposed on the stereo image sequence to establish correspondences. Next, we will roughly introduce the two methods, which are compared to each other later on.

2.1 Phase-Shifting Fringe Projection

The illumination design consists of two orthogonal sets of N phase shifted $1 + \cos(kx + \phi_n)$ patterns, with $k = \frac{2\pi}{p}$ (p is the period length of the fringe pattern) and the phase step $\phi_n = 2\pi\frac{n}{N}$. In order to establish correspondences a phase value $\phi^V(x,y)$ is calculated for every pixel of every view V of the image sequence by using

$$\phi^V(x,y) = \frac{\sum_{n=1}^{N} C_n^V \cos(2\pi\frac{n}{N})}{\sum_{n=1}^{N} C_n^V \sin(2\pi\frac{n}{N})} \quad , \tag{1}$$

where C_n^V represents the gray value sequence of the pixel (x,y) for an N-step phase shifting regime. After phase ambiguities are solved by other means, a correspondence is assigned by minimizing the phase differences for a given pixel (x,y) of view 1 within a local neighbourhood of a pixel (x',y') of view 2: $M = \min\left|\phi^1(x,y) - \phi^2(x',y')\right|$.

2.2 Statistical Band-Limited Pattern Projection (BLP)

For this method a set of $2N$ band-limited statistical patterns [7] is used. By choosing the appropriate frequency band, it is possible to adjust the structure sizes to a similar length scale compared to the fringe period of the phase-shifting regime. For the correspondence assignment of a given pixel (x,y) in view 1 the normalized cross correlation is calculated with pixels in the local neighbour of view 2

$$\rho(C_n^1, C_n^2) = \frac{\sum_{n=1}^{N}(C_n^1 - \overline{C^1})(C_n^2 - \overline{C^2})}{\sigma_{C^1}\sigma_{C^2}} \quad , \tag{2}$$

where $\overline{C^V}$ is the average value of C_n^V and σ_{C^V} is the standard deviation of C_n^V. The pixel of view 2, which correlates best is chosen as corresponding point: $M = \max \rho(C_n^1, C_n^2)$.

3 Similarities between both evaluation strategies

From the description of the previous section it is obvious, that both evaluation functions try to find the best match according to a certain matching criterion M. Thus, it interesting to see, which gray value sequence C_n^2 optimizes the evaluation strategies for a given sequence C_n^1.

For the BLP method, it can be easily seen that the correlation function is maximized ($M = 1$) for all

C_n^2 which satisfy $C_n^1 = mC_n^2 + b \wedge m, b \in R$. In case of the PSF method, it is evident that the matching function is minimized ($M = 0$) by gray value sequences yielding an identical phase value $\phi^1(x,y) = \phi^2(x',y')$. For an even N it can be shown, that the equivalence relation holds true:

$$\forall C_n^1 = mC_n^2 + b \wedge m, b \in R \Leftrightarrow \phi^1(x,y) = \phi^2(x',y'). \tag{3}$$

It can be concluded that both evaluation strategies are optimized for the same set of gray value sequences for a given reference gray value sequence, although their respective convergence properties towards that goal might be different. Nevertheless, it is plausible from that perspective that both evaluation strategies may lead to similar results.

4 Noise of the Correspondence Assignment

In order to show that both structured illumination approaches are comparable in their correspondence assignment accuracy, we simulated a stereophotogrammetric setup via a renderer. The chosen hardware was as follows: 640×480 pixels, focal length $f = 17.0mm$, pixel pitch $\Delta x = 7.6\,\mu\text{m}$, measurement volume $\approx (10 \times 10 \times 10)cm^3$ and a perfect plane as test-object. In total 96 different pattern projections were simulated: 48 band-limited patterns, 32 phase shifted fringe patterns and 16 gray code patterns. Afterwards, the correspondence assignment was conducted using a certain subset of these stereo-images. The standard deviation of the final 3D points to a plane fit to the point set was calculated as a measure for the correspondence assignment quality. The results are shown in figure 1.

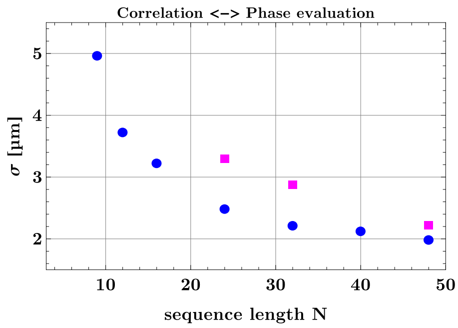

Fig. 1 *RMSD of the 3D points to a fitted plane using different sequence length*

The blue data points represent the results, when up to 48 band-limtited patterns are used to assign correspondences with the correlation method. The pink data points represent the results using 16 gray code patterns to resolve phase ambiguities, as well as up to 32 phase shifted fringe patterns (up to 16 fringes per orientation). From the results it can be concluded that both coding strategies delvier comparable correspondence assignment accuracies for a larger sequence length. Due to the necessity to have a gray code sequence for most phase-shifting fringe projection applications, statistical patterns perform slightly better for shorter sequence length.

Concluding, we have discussed that the different evaluation strategies for PSF and BLP have the same optimization goal and therefore both strategies should be able to reach comparable correspondence assignment accuracies. Furthermore, we conducted a simulation of a stereophogogrammetric setup and discussed the noise of the resulting 3D points, which actually showed that both methods reach a comparable noise level.

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