EDEVELOPMENT OF EFFECTIVE PROCEDURES FOR AUTOMATIC STEREO MATCHING

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ABSTRACT:

It is well known that the correlation stereo matching algorithms are the basis of most of digital photogrammetric systems. This paper concerns the important problem of increasing of computational speed of automatic stereo matching based on elimination of image parts with low information presence and non-traditional implementation of computations using the “sliding window” technique.

1. INTRODUCTION

It is well known that the correlation stereo matching algorithms are the basis of most of digital photogrammetric systems. This paper concerns the important problem of increasing of computational speed of automatic stereo matching based on image informative characteristics and non-traditional implementation of computations in a sliding correlation window.

From our experience of operation with well known Russian TK-350 spaceborn images (Sibiryakov, 2000), they usually include some low-informative regions. Stereo matching of such regions is just a waste of time. Therefore there is a problem of selection of sample regions from the viewpoint of their selfdescriptiveness under the criterion of accuracy and probability of correct stereo matching. At use of correlation methods, a correlation coefficient is the best characteristic of a signal level inside template. The disadvantage of this characteristic that it is calculated during matching, while the index of signal level should be calculated before matching, indicating on those templates, which will have accurate matching. In the developed method an adaptive statistics of template brightness is used as an a priori evaluation of informative index, which is similar to the correlation coefficient. An advantage of this index is that it is calculated prior to the beginning of matching. This problem is considered in the section 2 of this paper.

Then the problem of reduction of computational time is considered concerning the automatic stereo matching based on the normalized correlation. The idea of acceleration of calculation of the convolution sums in a sliding window is well known (Huang, 1983). The essence of this idea consists of storing the ready-made column sums and recursive subtracting and adding of the appropriate partial sums corresponding to the motion of a sliding window along the image row. It allows essentially reducing the amount of calculations in case of usual correlation convolutions, but not in case of stereo matching with separate convolution fields for all image points. In this work it is offered to bypass this problem by means of changing the order of calculations. It is proposed to implement the loop by disparities as an external loop, and the convolution loop as an internal one. In this case all calculations can be implemented in a manner of sliding window algorithm, and we obtain the required gain in productivity. This problem is considered in the section 3 of this paper.

2. ANALYSIS OF SELFDESCRIPTIVENESS OF IMAGE FRAGMENT

The proposed method for elimination of “empty places” is based on analysis of brightness statistical properties of the special “wedge” (Figure 1) also captured by this camera. The “wedge” here is an image with smoothed intensity changing from left to right border. Analysis method contains the following.

The smoothed functions of intensity B(d) and MSE of intensity D(d) along the “wedge” are obtained.

Then the dependence of noise MSE on intensity D(b) is estimated. For this purpose one should create the inverse function $d=B^{-1}(b)$ using the linear interpolation. Then the function has a form

$$D(b) = D^{*}(B^{-1}(b)). \qquad (1)$$

shown on Figure 2.

Function $\sigma^2 = D(b)$ allows testing the signal presence in the image fragment.

Figure 1. The optical “wedge” image.

Let f_i – means the value of signal samples inside the fragment, $i=1,...,(2N+1)(2N+1)$. It is required to test the hypothesis H_0 concerning the data set is homogeneous:

$$H_0: \qquad f_i = u + n_i , \qquad n_i \in N(0,\sigma^2(u)),$$

where u is the supposed constant brightness value on a fragment; n_i – noise samples, $\sigma(u)$ –dependence of MSE on intensity, derived from the “wedge”.

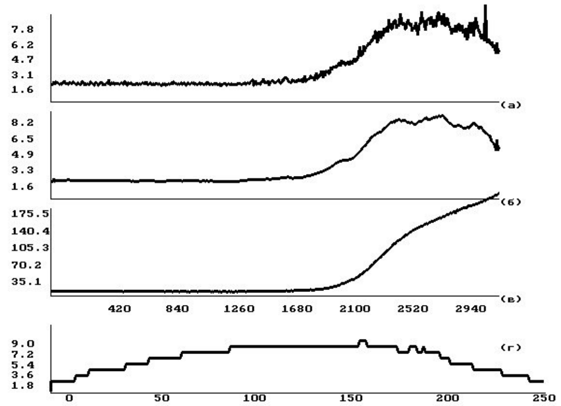

Figure 2. Analysis of statistical properties of noise by the "wedge" image: a – noise variance along the "wedge"; b – smoothed noise variance; c – changing of intensity along the "wedge" d – dependence of noise variance on intensity.

Hypothesis H_0 is equivalent for the following:

$$H_0: \quad f_i = \xi_i, \quad \xi_i \in N(u, \sigma^2(u))$$

For variance

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N} f_i^{\,2} - \left(\frac{1}{N}\sum_{i=1}^{N} f_i\right)^2 \tag{2}$$

it is known, that the value $\frac{(N-1)\sigma^2}{\sigma^2(u)}$ satisfies to χ^2 – distribution with (N-1) degrees of freedom. So, H_0 is equivalent to the following expression:

$$H_0: \quad s = \frac{(N-1)\sigma^2}{\sigma^2(u)} \in \chi^2(N\text{-}1), \tag{3}$$

The estimation of value is formed as follows:

$$u = \frac{1}{N}\sum_{i=1}^{N} f_i. \tag{4}$$

Then, since statistics are calculated, the criterion of signal presence is tested as follows:

$$\text{If } s \geq \chi^2(N\text{-}1)$$

then H_0 hypothesis to be rejected.

For N > 30 the quantile of χ_p^2 distribution can be estimated by formula

$$\chi_p^{\,2}(m) = \frac{1}{2}\left(\sqrt{2m-1} + \alpha_p\right)^2,$$

where α_p - the quantile of normal distribution.
Thus, the decision rule has the form:

$$\frac{(N-1)\sigma^2}{\sigma^2(u)} \geq \frac{1}{2}(\sqrt{2(N-1)-1} + \alpha_p)^2,$$

which is equivalent to

$$\frac{\sigma}{\sigma(u)} \geq \frac{1}{\sqrt{2(N-1)}}(\sqrt{2(N-1)-1} + \alpha_p) \approx 1 + \frac{\alpha_p}{\sqrt{2(N-1)}}.$$

So, the decision rule takes the form:

$$\text{If} \quad \sigma \geq (1 + \frac{\alpha_p}{\sqrt{2(N-1)}})\sigma(u),$$

then H_0 hypothesis to be rejected.
Because it is useful to process data sets with *N*>200, this criterion is applied in the following form:

$$\sigma \geq (1 + \frac{C}{\sqrt{N}})\sigma(u),$$

where $C = \frac{\alpha_{0995}}{\sqrt{2}} \approx 2.4$.
So, the thresholding becomes adaptive. It depends both on the testing set amount, and on the statistical properties of the signal inside the image fragment. If one use the informative function

$$I(x_0, y_0, N) = \sigma(x_0, y_0, N),$$

then the threshold T is obtained as

$$T = (1 + \frac{C}{\sqrt{N}})\sigma(u) \tag{5}$$

3. FAST ALGORITHM FOR STEREO CORRELATION BASED ON A "SLIDING WINDOW" METHOD

In this part of the paper the problem of reduction of computational time is considered for the automatic stereo matching based on the normalized correlation.

Let we have two grayscale digital stereo images of 3D scene: $g_l(x,y)$ and $g_r(x,y)$. Let consider for each pixel from left image the rectangle $\Omega = [left, right] \times [top, bottom]$ of size *MxN*. It is required to find the best corresponded pixels on the right image. Standard solution of stereo correspondence problem is obtained by means of normalized stereo correlation $corr(x_l,y_l;x_r,y_r)$ for pixels (x_l,y_l) and (x_r,y_r):

$$= \frac{c-d}{e*f} \quad (6)$$

where

$$c = \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l(x_l + x, y_l + y) g_r(x_r + x, y_r + y) ,$$

$$d = \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l(x_l + x, y_l + y) \cdot \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_r(x_r + x, y_r + y) ,$$

$$e = \sqrt{\sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l^2(x_l + x, y_l + y) - \left(\sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l(x_l + x, y_l + y) \right)^2} ,$$

$$f = \sqrt{\sum_{x=-a}^{a} \sum_{y=-b}^{b} g_r^2(x_r + x, y_r + y) - \left(\sum_{x=-a}^{a} \sum_{y=-b}^{b} g_r(x_r + x, y_r + y) \right)^2}$$

and where $(2a+1) \times (2b+1)$ – the size of correlation region. For the best matching it is necessary to find:

$$\left(x_r(x_l,y_l), y_r(x_l,y_l)\right) = \underset{|x_l - x_r| \le \Delta x_{\max}, |y_l - y_r| \le \Delta y_{\max}}{\arg\max} corr\left((x_l,y_l);(x_r,y_r)\right) \quad (7)$$

The key idea of acceleration of calculation for expression (6) is the use the "sliding window" algorithm like analogous sliding window algorithms for sum accumulation described by Huang (Huang, 1983). The essence of this idea consists of storing the ready-made column sums and recursive subtracting and adding of the appropriate partial sums corresponding to the motion of a sliding window along the image row.

In order to apply this idea to normalized stereo correlation computation, let rewrite the expression (6) with the following additional notation:

$$s_{ll}(x_l, y_l) = \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l^2(x_l + x, y_l + y) , \quad (8)$$

$$s_r(x_r, y_r) = \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_r(x_r + x, y_r + y) , \quad (9)$$

$$s_{rr}(x_r, y_r) = \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_r^2(x_r + x, y_r + y) , \quad (10)$$

$$s_{lr}(x_l, y_l; x_r, y_r) = \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l(x_l + x, y_l + y) g_r(x_r + x, y_r + y) , \quad (11)$$

where $(x_l, y_l) \in [left, right] \times [top, bottom]$,
$(x_r, y_r) \in [left - \Delta x_{\max}, right + \Delta x_{\max}] \times [top-1, bottom+1]$.

Then

$$corr(x_l, y_l; x_r, y_r) = \frac{s_{lr}(x_l, y_l; x_r, y_r) - s_l(x_l, y_l) s_r(x_r, y_r)}{\sqrt{\left(s_{ll}(x_l, y_l) - s_l^2(x_l, y_l)\right) \cdot \left(s_{rr}(x_r, y_r) - s_r^2(x_r, y_r)\right)}} \quad (12)$$

It is easy to see, that $s_l(x_l, y_l)$, $s_{ll}(x_l, y_l)$, $s_r(x_r, y_r)$, $s_{rr}(x_r, y_r)$ can be previously computed by sliding window algorithm before the main loop is started. However, it is not enough for essential acceleration of stereo correlation because the computation of $s_{lr}(x_l, y_l; x_r, y_r)$ still require $O(a \cdot b \cdot \Delta x_{\max} \cdot M \cdot N)$ of operation. To accelerate this stage, let transform the formula (11) as follows:

$$\tilde{s}_{lr}(x_l, y_l; \Delta x, \Delta y) \equiv s_{lr}(x_l, y_l; x_l + \Delta x, y_l + \Delta y) =$$
$$\sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l(x_l + x, y_l + y) g_r(x_l + \Delta x + x, y_l + \Delta y + y) =$$
$$= \sum_{x=-a}^{a} \sum_{y=-b}^{b} g_l(x_l + x, y_l + y) \tilde{g}_r(x_l + x, y_l + y; \Delta x, \Delta y) , \quad (13)$$

where
$\tilde{g}_r(x_l + x, y_l + y; \Delta x, \Delta y) = g_r(x_l + x + \Delta x, y_l + y + \Delta y)$

From (13) one can see, that under the fixed Δx and Δy values $\tilde{s}_{lr}(x_l, y_l; \Delta x, \Delta y)$ for $(x_l, y_l) \in \Omega$ can be computed by the "sliding window" algorithm approximately by

$$2(2 + k_0 + k_*) \cdot b \cdot N \cdot M \quad (14)$$

of operations.

Thus, if we change the order of loops by (x_l,y_l) and $(\Delta x, \Delta y)$, and use the "sliding window" method, the complexity of this algorithm can be estimated as:

$$4(2 + k_0 + k_*) \cdot b \cdot N \cdot M + \left[2b \cdot (2k_0 + k_* + 1) + 3 + 4k_* + k_l + k_{\sqrt{}}\right] \cdot N \cdot M \cdot 3 \cdot 2\Delta x_{\max} \approx$$
$$\approx 12(2k_0 + k_* + 1) \cdot b \cdot N \cdot M \cdot \Delta x_{\max} \quad (15)$$

of operations (supposing that $\Delta x_{\max} >> 1$).

So, we obtain the modified algorithm with the computational complexity decreased in *2a* times relative to traditional scheme. It is also important that the algorithm described can be easily implemented at any parallel architecture.

4. CONCLUSIONS

The problem of increasing of computational speed of automatic stereo matching is an important issue for designing low cost photogrammetric systems on PC-compatible computers. In this paper the solution for this problem is proposed based on image informative characteristics and non-traditional implementation of computations in a sliding correlation window.

Both useful described techniques allows obtaining the economy of computational time up to 20-25 times while processing of typical Russian TK-350 spaceborn images, and could be used for another data processing schemes.

REFERENCES

Sibiryakov A., 2000. DTM generation from Russian TK-350 space imagery in the PC-based photogrammetric system Z-Space, *International Archives of Photogrammetry and Remote Sensing*, Vol.XXXII, Part B4, Amsterdam.

Huang T.S., 1983. *Image Sequence Processing and Dynamic Scence Analysis.* – Springer-Verlag, New York.