The box filter of size 9×9 is an approximation of a Gaussian with $\sigma = 1.2$ and represents the lowest level (highest spatial resolution) for blob-response maps.

V. SUM OF SQUARE OF DIFFERENCE FEATURE POINTS TRACKER

Sum of square difference was another matching technique where matching was done pixel-by-pixel or in other word, pixel-based matching. The concept of 'sum of square difference matching algorithm' is implemented left and right images. A template with suitable size was moved in the search window to locate and match its conjugate points. The size of the searching window must be larger than the template window. The template with suitable size must be smaller than the size of the search window (for example, template of 3 × 3 and search window of 7 × 7 pixels and lines). The equation for SSD matching algorithm can be expressed as:

$$SSD = \sum \left(f_o(x+j) - f_i(x+j+d_i) \right)^2, \qquad (12)$$

where SSD is 'sum of square difference' value, f_o is template Grey-level matrix; f_i is search window in Greylevel matrix, x is height of template and j is width of template. The 'sum of square difference' is applied to determine the difference of data observed with the data tested. This was because the residual errors obtained from point selected could be calculated to determine the best fit. Sum square of difference method had become a powerful tool in image matching. Not only for determination of difference of points, the SSD method was capable of extinguishing the correlation between both data. The basic equation of 'least square' could be determined in Equation (12).

VI. INPUT DATA

As an input for testing efficiency of algorithms a pair of images was considered (Fig. 2).

For proper functioning of algorithms, this images must first be undistorted to prevent warping of objects(Fig. 3).

Here we can see a pair of undistorted images taken from a distance to the center of the image of 1.6 m and a basis of 10 cm.

Fig. 2. Initial input images

Fig. 3. Undistorted images

VII. EIGENVALUE CORNER DETECTION WITH SSD POINT MATCHING

This pair of methods were considered the first. They showed great accuracy in feature points extraction and matching, which is perfect for relief reconstruction, although due to extremely slow working speed it was considered as unsuitable (Fig. 4).

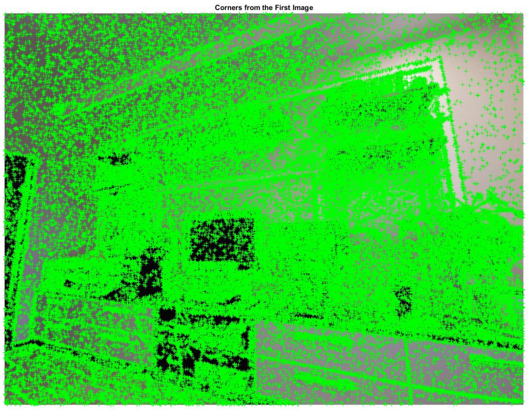


Fig. 4. Detected corners on the first image

As we can see, the amount of detected corners on the first image is high (72316 points), which contributes to the accuracy of the algorithm but at the same time, the increased amount of points negatively influences speed of execution (Fig. 5).

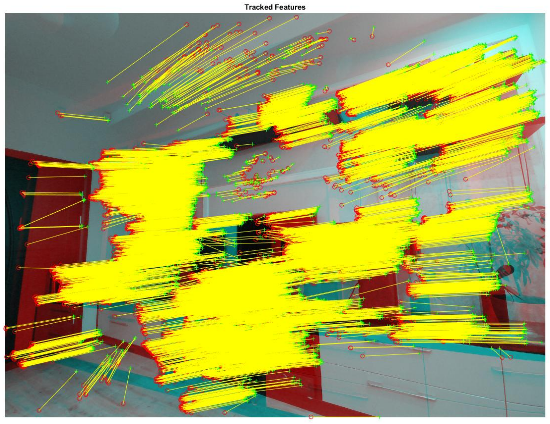


Fig. 5. Matched features

As the principle of SSD matching algorithm is comparing every point of the first image to every point of second image in certain block it takes a while to handle this amount of points (Fig. 6).

After the points triangulation, using DLT algorithm, scene relief is pretty accurate and the main objects of interest are distinct. Amount of points on this reconstruction is 10811 (Fig. 7).

After points triangulation, the reprojection errors of each point is considered, with this method having only 237 out of 10811 points having reprojection error more than 20 pixels, which is 2.2% (Fig. 8)!

Fig. 6. Point cloud of reconstructed scene

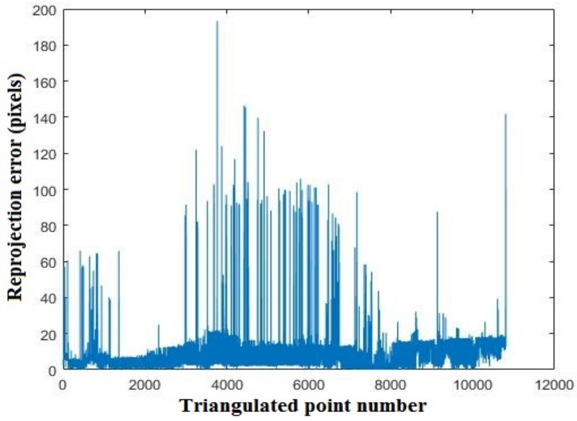


Fig. 7. Reprojection error graph

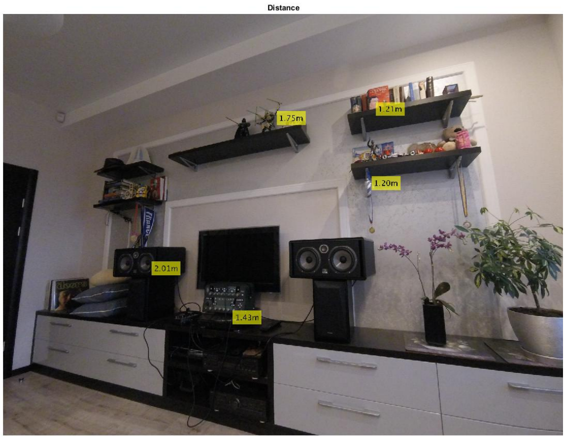
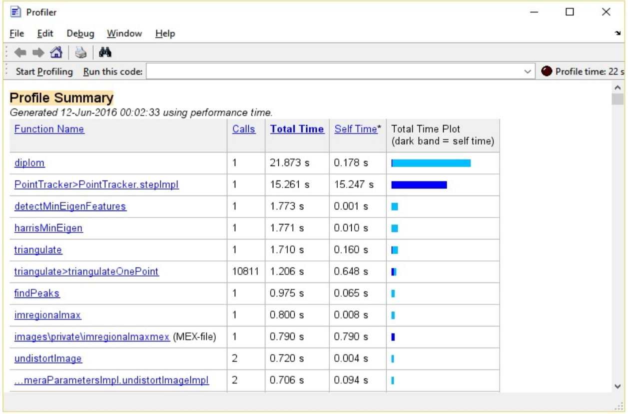


Fig. 8. Computed distances to 5 random points

Distance is calculated as the mean of Z coordinates of points, so the mean distance to the objects of picture is 1.27 m, which is very close to the etalon distance with deviation of only 17 centimeters (Fig. 9).

The algorithm required 21.873 s to compute all data, which is unacceptable for a real-time height estimation. Main resource hog of the algorithm being PointTracker step function, which is the realization of SSD point matching as well as ~ 5–7 s where spent on plots and pictures.



Profile Summary

Generated 12-Jun-2016 00:02:33 using performance time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
diplom	1	21.873 s	0.178 s	
PointTracker>PointTracker.stepImpl	1	15.261 s	15.247 s	
detectMinEigenFeatures	1	1.773 s	0.001 s	
harrisMinEigen	1	1.771 s	0.010 s	
triangulate	1	1.710 s	0.160 s	
triangulate>triangulateOnePoint	10811	1.206 s	0.648 s	
findPeaks	1	0.975 s	0.065 s	
imregionalmax	1	0.800 s	0.008 s	
images\private\imregionalmaxmex (MEX-file)	1	0.790 s	0.790 s	
undistortImage	2	0.720 s	0.004 s	
...meraParametersImpl.undistortImageImpl	2	0.706 s	0.094 s	

Fig. 9. Working time profile

VIII. HARRIS CORNERS DETECTION WITH SSD POINTS MATCHING

To decrease working time, another method of feature points extraction was considered. Although, due to algorithm specifics it finds less points, it works considerably faster than Eigenvalue (Fig. 10).

Fig. 10. Detected features on the first image

As this algorithm being much more precise corner detector, it finds considerably lower amount of feature points (1578) which even further decreases operation time, as SSD will have less points to match (Fig. 11).

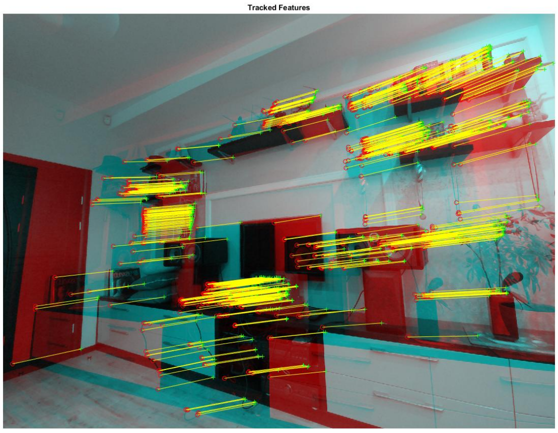


Fig. 11 Tracked features

Algorithm resulted in 758 matched points which is considerably lower than previous pair of algorithm, making this pair inferior in relief reconstruction task (Fig. 12).

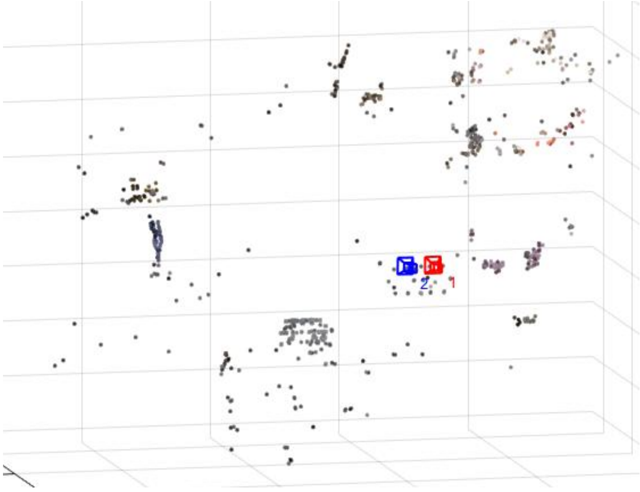


Fig.12. Point cloud of reconstructed scene

Results of DLT reconstruction are not so distinct, although form of the objects can be estimated (Fig. 13).

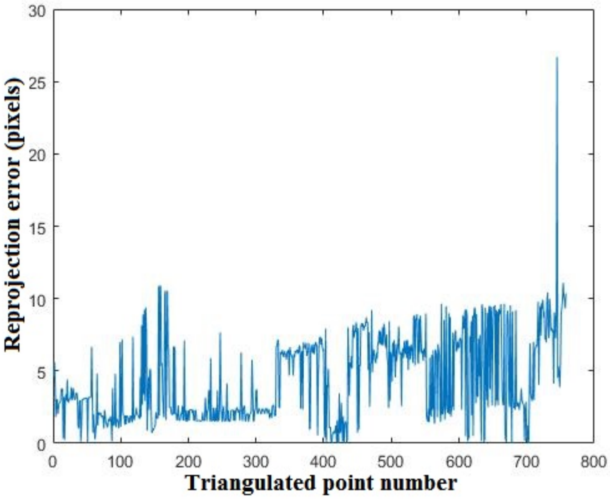


Fig. 13. Reprojection error graph

Precision of this method is one of the highest, as points with reprojection error of over 20 is only 1 out of 758, which is 0.13%. This precision is highly valuable in estimation of height (Fig. 14).

Mean distance to the objects of the scene is 1.47, which is very close to the etalon of 1.6 m (Fig. 15).

Working time of this pair is almost two times lower than MinEigen+SSD, this is achieved by faster algorithm of feature points tracking as well as less amount of points to operate with for SSD algorithm. Previously considered the most resource inefficient function of PointTracker step in this pair takes less that a second to compute its results.

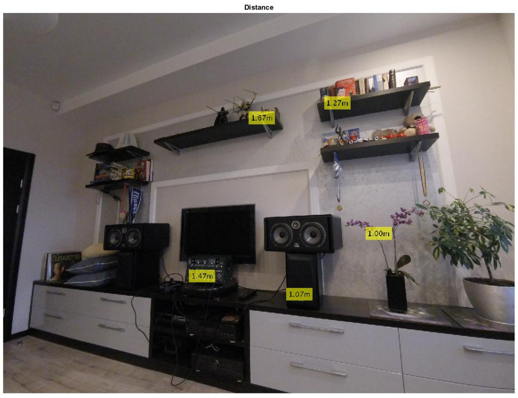
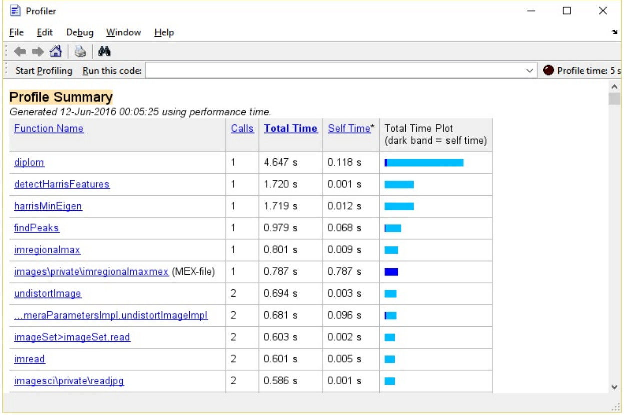


Fig. 14. Computed distances to 5 random points



Profile Summary

Generated 12-Jun-2016 00:05:25 using performance time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
diplom	1	4.647 s	0.118 s	
detectHarrisFeatures	1	1.720 s	0.001 s	
harrisMinEigen	1	1.719 s	0.012 s	
findPeaks	1	0.979 s	0.068 s	
imregionalmax	1	0.801 s	0.009 s	
images\private\imregionalmaxmex (MEX-file)	1	0.787 s	0.787 s	
undistortImage	2	0.694 s	0.003 s	
...meraParametersImpl.undistortImageImpl	2	0.681 s	0.096 s	
imageSet>imageSet.read	2	0.603 s	0.002 s	
imread	2	0.601 s	0.005 s	
imagesci\private\readjpg	2	0.586 s	0.001 s	

Fig. 15. Working time profile

IX. SURF FEATURE POINT DETECTION AND SSD FEATURE MATCHING

To decrease working time, another method of feature points extraction and matching was considered. Although, due to algorithm specifics it finds less points, it works considerably faster than Eigenvalue. This method is very inefficient in terms of relief recovery, as it finds less matched points (Fig. 16).

Fig. 16. Detected descriptors on the first image

The amount of features tracked was good enough to start with. As SURF is a descriptor tracker, it outputs regions (blobs) that differ in properties such as brightness or color, compared to surrounding regions (Fig. 17).

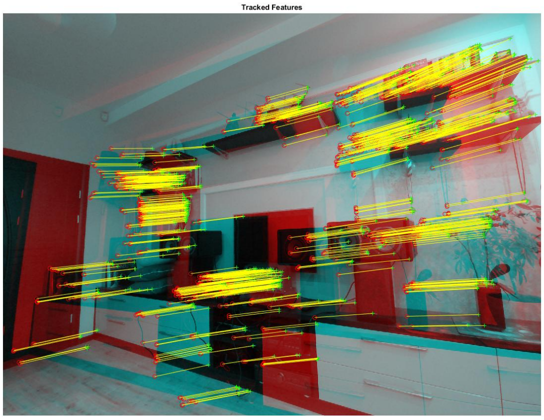


Fig. 17. Tracked SURF features

The amount of matched points is lower than in any other method, that were investigated. That's due to SURF being very sensitive to warping and brightness changes, even very small brightness fluctuation during photographing can lead to poor features matching (Fig. 18).

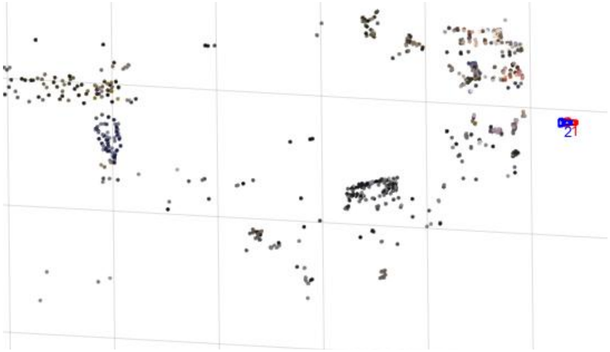


Fig. 18. Point cloud of reconstructed scene

That being said, relief reconstruction is hard using SURF, as the matched points are the crucial part of triangulation. Points cloud is scattered and objects are indistinctive (Fig. 19).

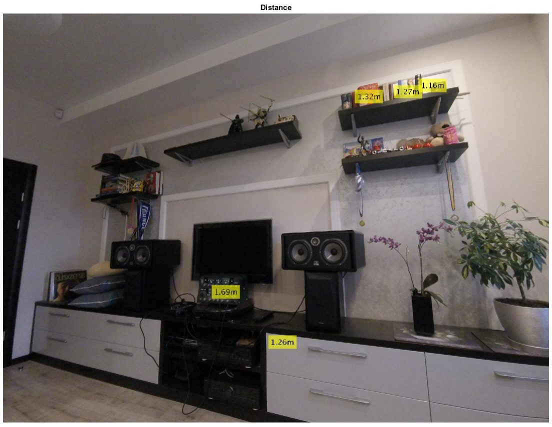


Fig. 19 Computed distances to 5 random points

Distance estimation is fairly accurate in this method as it deviates from etalon for 0.09 m, as estimation of distance can be made even with one matched point (Fig. 20).

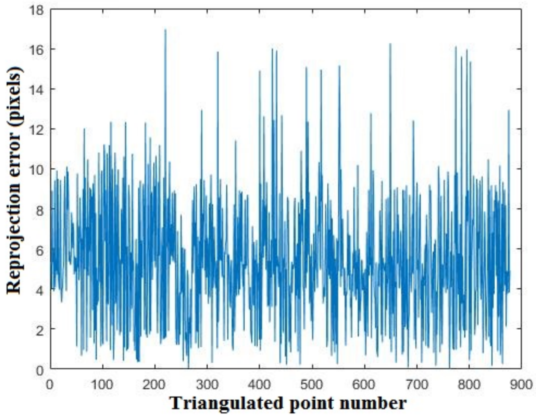
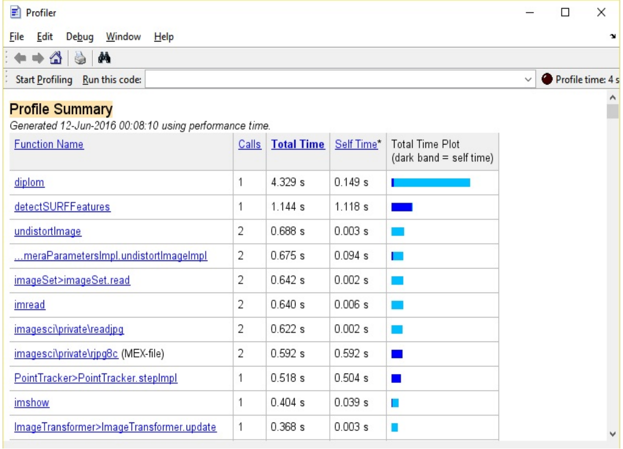


Fig. 20. Reprojection error graph

In current situation, SURF showed itself as very efficient method for our purposes. In 877 matched points, 0 of them had reprojection error over 20 pixels (Fig. 21).



Profile Summary

Generated 12-Jun-2016 00:08:10 using performance time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
diplom	1	4.329 s	0.149 s	
detectSURFFeatures	1	1.144 s	1.118 s	
undistortImage	2	0.688 s	0.003 s	
...meraParametersImpl.undistortImageImpl	2	0.675 s	0.094 s	
imageSet>imageSet.read	2	0.642 s	0.002 s	
imread	2	0.640 s	0.006 s	
imagesci\private\readjpg	2	0.622 s	0.002 s	
imagesci\private\rjpg8c (MEX-file)	2	0.592 s	0.592 s	
PointTracker>PointTracker.stepImpl	1	0.518 s	0.504 s	
imshow	1	0.404 s	0.039 s	
ImageTransformer>ImageTransformer.update	1	0.368 s	0.003 s	

Fig. 21. Working time profile

Working time was just above of Harris+SSD method, which makes it objectively worse.

X. RECOMMENDATIONS AND CONCLUSIONS

This work introduces correlation stereoscope recognition of flight data. It has been shown the necessity of such system usage in UAV navigation complex structure. For collective use of correlation stereoscope recognition system, it is necessary to develop methods of joint information processing. It has been researched such methods as Harris corner detector, SURF, Mineigenvalue (for feature points extraction), SSD (for matching feature points) and DLT (for matched points triangulation and distance estimation). It has been also illustrated that they are suitable to work in real-time conditions. Three pairs of algorithms were investigated in terms of usability in real-time on-board system, for height estimation as well as relief reconstruction. On the one hand method of MinEigenvalues can be considered the best for relief reconstruction, as it returns the largest amount of matched points with fairly low reprojection errors. Objects on the reconstructed scene are distinct and relief is accurate. On the other hand, the operation time for this algorithm is too long for real-time work, also its height estimation error was the highest, approximately 17 cm.

It’s reasonable to consider Harris corner detection to be very efficient method for our system as it has decent accuracy for height estimation (error in less than 13 cm) as well as close enough relief reconstruction. It’s operation time is suitable for real-time calculations, which makes it the perfect fit.

After researching of all three methods, it is clear that the most overall effective method is SUR feature tracking with SSD points matching, as it showed itself as fast and reliable method of height estimation and overall surpassed Harris method in both height and relief estimation as well as time spent. It has been researched (Table I) such methods as Harris corner detector, SURF, Mineigenvalue (for feature points extraction), SSD (for matching feature points) and DLT (for matched points triangulation and distance estimation).

TABLE I

COMPARISON CHARACTERISTICS OF DIFFERENT METHODS

Algorithm name	Working time (s)	Points tracked	Points matched	Reprojection errors over 20 pixels (%)	Deviation in distance estimation (m)
MinEigen	21.873	72316	10811	2.2	-0.17
Harris	4.647	1578	758	0.13	-0.13
SURF	4.329	2041	877	0	+0.09

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М. П. Мухіна, М.І. Панарін. Алгоритм кореляційного стереоскопічного розпізнавання

Розглянуто кореляційне стереоскопічне розпізнавання. Розроблено програмне забезпечення, за допомогою якого обробляються польотні дані, отримані з БПЛА. Проведено моделювання руху БПЛА з камерою на борту та отримано фотографії, які оброблялися різними методами, у результаті чого були зіставлені особливі точки та тріангульовані для створення 3D-рельєфу. Результати дослідження показали, що ймовірність розпізнавання відповідає вказаним рівням, навіть якщо зображення спотворене. Використання запропонованого алгоритму кореляційного стереоскопічного розпізнавання можливе для оцінювання висоти у реальному часі і відновлення рельєфу.

Ключові слова: виявлення кутів; метод Харріса; SURF; метод прямого лінійного перетворення; КЛТ; відновлення рельєфу; тріангуляція; стерео бачення; стереовідповідність.

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М. П. Мухина, М. И. Панарин. Алгоритм корреляционного стереоскопического распознавания

Рассмотрено корреляционное стереоскопическое распознавание. Разработано программное обеспечение, с помощью которого обрабатываются полетные данные, полученные с БПЛА. Проведено моделирование движения БПЛА с камерой на борту и получены фотографии, которые обрабатывались различными методами, в результате чего были сопоставлены особые точки и триангулированы для создания 3D-рельефа. Результаты исследования показали, что вероятность распознавания соответствует указанным уровням, даже если изображение искажено. Использование предложенного алгоритма корреляционного стереоскопического распознавания возможно для оценивания высоты в реальном времени и восстановления рельефа.

Ключевые слова: выявление углов; метод Харриса; SURF; метод прямого линейного преобразования; КЛТ, восстановление рельефа; триангуляция; стерео зрение; стереосоответствие.

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