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APPLICATION OF DISCRETE CROSS-CORRELATION FUNCTION FOR OBSERVATIONAL-COMPARATIVE NAVIGATION SYSTEM

ABSTRACT

The article presents navigation system project operating on the principle scene matching area correlation (SMAC), using a digital camera, an MEMS e-compass sensor and an ultrasonic ranging module. Systems of this type are used as a component of advanced integrated navigation systems in view of its autonomy and capability of localizing aircrafts with high accuracy and precision. Steering and display of information are implemented using a computer application designed in Matlab programming environment. The object's location is fixed, using discrete cross-correlation function through matching of the registered terrain image to digital orthophotomap.

The article describes operations directly related to digital image processing, its implementation methods, a structural system design with explanations of each of the functional elements and presents devices used to build a complete integrated measurement unit model. It was used for the effectiveness measurement of determining the location of an object depending on the changes of angle and height of the flight as well as the luminance and noise level in a registered image. The measurements methodology was described which also includes an analysis of the results, an effectiveness evaluation and potential development directions of the designed system.

Keywords:
navigation system, discrete cross-correlation function.

INTRODUCTION

One of the directions of navigation systems development is to strive to improve the accuracy of location of the object, while maintaining their autonomy. It means that the appointment of the state vector containing information about the position and velocity is based on the resources available on board of the aircraft [Łabowski, Kaniewski, Konatowski, 2016]. The use of distance travelled counting systems such as an inertial navigation system INS [Woodman, 2007] is associated with error increasing in time, due to the operation of sensors included in the inertial measurement unit IMU, such as a gyroscopes and accelerometers.

To ensure constant high precision and accuracy of determining the location of an object, it needs to periodically make some adjustments to the system. For this purpose integrated navigation systems that base their operations on at least two independent systems are formed. In the case of cooperation of the inertial system with the positioning system such as satellite systems (GPS, Galileo, GLONASS, etc.) [Rao, 2010] or radio navigation (VOR, DME, TACAN, etc.) [Polak, Rypulak, 2002], for the correct operation is required to receive signals from satellites or ground-based radio beacons.

Another solution is to integrate in an observational-comparative navigation system matching image area to pattern SMAC (Scene Matching Area Correlation) [Titterton, Weston, 2004]. This allows for maintaining full autonomy while ensuring adjustment for the INS system. The accuracy of determining the location of the systems SMAC already in 1997 was estimated at 1–2 m [Narkiewicz, 1999]. The rapid increase of computer power and available computer memory in recent years could further improve their properties.

Operation of SMAC can be compared to the role of a navigator, who observing the area under the aircraft is able to determine the location in space based on information from the on-board sensors (altimeter, magnetic compass) and information about the area he is moving on. The principle of how the system operates is depicted in Figure 1.

In the automated process a computer performs a comparison of the recorded image area with the reference image it is digital mapped area stored in the system memory.

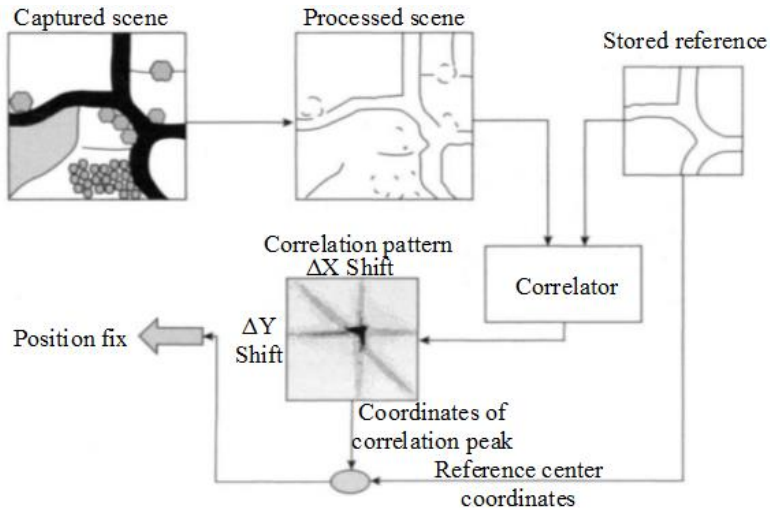

Fig. 1. The principle of SMAC [Titterton, Weston, 2004]

This article presented the use of discrete 2D cross-correlation function to determine the point of maximum matching of these two images. This operation allows to determine localization of the object in a two-dimensional space. Additionally, thanks to the information about altitude from on-board devices, it is possible to locate in three-dimensional space.

IMAGE PROCESSING FOR SMAC SYSTEMS

Before comparing the two images it is necessary to carry out pre--processing, with an aim to prepare the recorded image for a correlation process. The basis for a correctly matched registered image should be saved with the resolution and orientation according to the digital map. In the proposed system, the processing is carried out in Matlab for monochrome grayscale image, but the comparative operation is performed on binary images.

A digital camera, which acts as an on-board recorder, is being used for image acquisition. This prevents a perfect match, because the resulting image will always be to some extent degraded relative to the pattern. Differences are mainly due to the quality of the equipment used (contrast, resolution, sensor noise, geometric errors) and changing weather conditions (illumination, shadows) between moment of registration of images which consist of a digital map and the time of acquisition with on-board recorder.

Knowing that the digital camera in use has difficulty with registration and correct recording of extreme intensity levels, the proposed system was carried out correcting the contrast of the output using the *imadjust* method. An example of this method's application is displayed in Figure 2.

a) b)

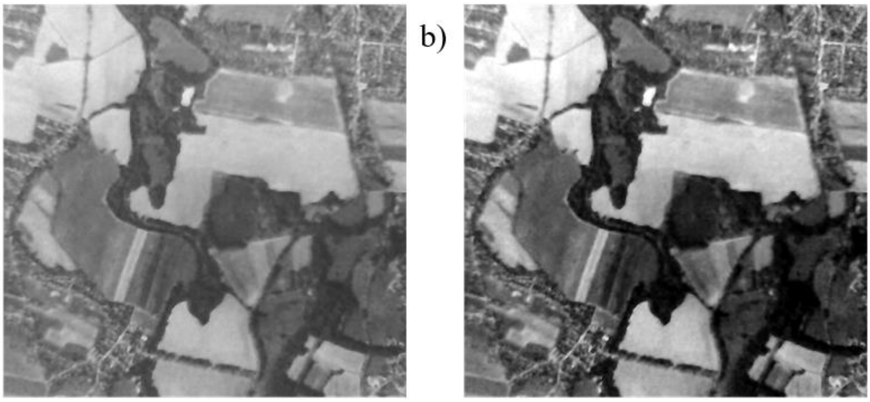

Fig. 2. Adjust image intensity values: a) registered image by digital camera, b) image after enhancing contrast (*imadjust*) [Grzywacz, 2016]

Another important step in the processing is to scale the image size so that the area recorded in the picture saved with spatial resolution equals the corresponding fragment on a digital map. Any change in this parameter reduces the image detail, which may result in its total distortion. Therefore the digital camera used in the proposed system, which is configured to record image with a constant spatial resolution (720 x 720 pixels) needs to be changed to capture an image with resolution depending on the height at which the recorder is situated.

To resize the digital image an *imresize* method is used, which allows to change the spatial resolution to a preset value. An example of correction is shown in Figure 3.

In carrying out the project approximating polynomial of the image's target resolution of image (*z* x *z*) representing a registered area as a function of altitude was determined. For this purpose, the area image was recorded at a different height of the recorder above printout of the digital map and then they were subjected to a manual match. The results are displayed in Table 1.

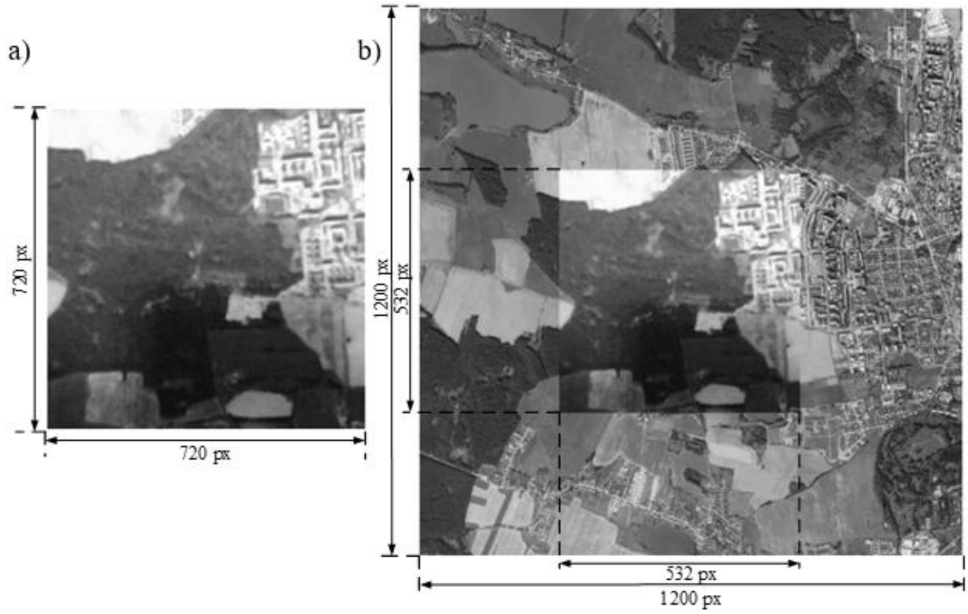

Fig. 3. Spatial resolution correction: a) image after *imadjust*, b) image after *imresize* and matching to the digital map [Grzywacz, 2016]

Tab. 1. Target image size value as a function of altitude $z = f(h)$ [Grzywacz, 2016]

h [mm]	50	60	71	80	90	100	111	122	132	147
z [px]	314	373	438	495	534	609	681	745	831	914
h [mm]	158	169	180	193	206	218	227	239	250	290
z [px]	978	1060	1113	1196	1298	1343	1441	1464	1511	1757

Subsequently, approximating the values obtained using the least squares polynomial scaling was determined during the sample interval altitude [Grzywacz, 2016]:

$$z(h) = 140.7531 + 1.7604 \cdot h + 0.04395 \cdot h^2 - 0.00017 \cdot h^3, \qquad (1)$$

where:
z — target image size value,
h — the height at which the on-board recorder.

Knowing the scale of the digital map, it is possible to calculate the actual operating range of altitude of the proposed system. The results of matching of the image to the pattern depend largely on the rescaling of the image level and geometric distortion entering through the lens of the on-board recorder. The minimum scaling-up is realized for the height ~117.1 mm, and any deviation from this value increases the rescaling level. To get high efficiency to match the images correctly in a wide altitude range, the digital camera resolution configuration should be changed as a function of the height at which the recorder is situated, thereby reducing the impact of scaling on the detection result.

Ensuring the correct registered image orientation with respect to the pattern is realized by compensating yaw angle of the object, resulting from the on-board equipment. For this purpose a method *imrotate* was used, which rotates the image by the compensation angle, defined by the following formula [Grzywacz, 2016]:

$$\beta = -\alpha\,, \tag{2}$$

where:

α — yaw angle $(\alpha \in (0^\circ, 360^\circ))$,

β — compensation angle $(\beta \in (-360^\circ, 0^\circ))$.

As a result of the operation performed the resulting image will have greater spatial resolution, which is important to carry out discussed correction in a proper order. Example of compensation of the yaw angle is shown in Figure 4.

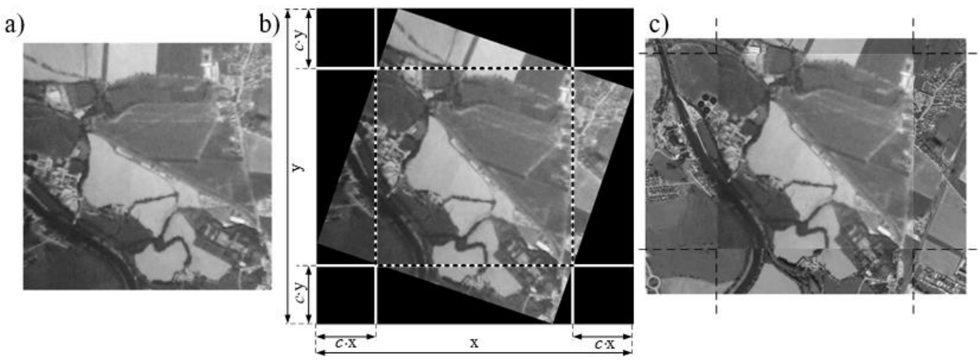

Fig. 4. Angle correction 19^o: a) processed image, b) compensation yaw angle before removing the edges, c) matching to the digital map [Grzywacz, 2016]

As a result of image rotation the part of the new image was filled with zeros (Fig. 4b). Columns and rows with this filling were removed from the image using the edge removing rate *c*, which is changing as a function of yaw angle shown in Figure 5. It has been determined empirically by manually checking the fill in the resulting image.

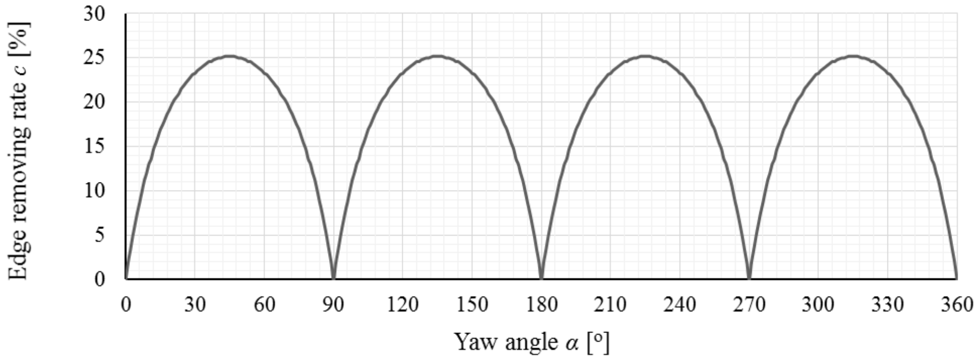

Fig. 5. Edge removing rate as a function of yaw angle $c = f(\alpha)$ [Grzywacz, 2016]

In order to optimize processing time and reduce the area of the possible error occurrence in the usage of a dynamic narrowing searching area function is proposed. Operation is shown in Figure 6.

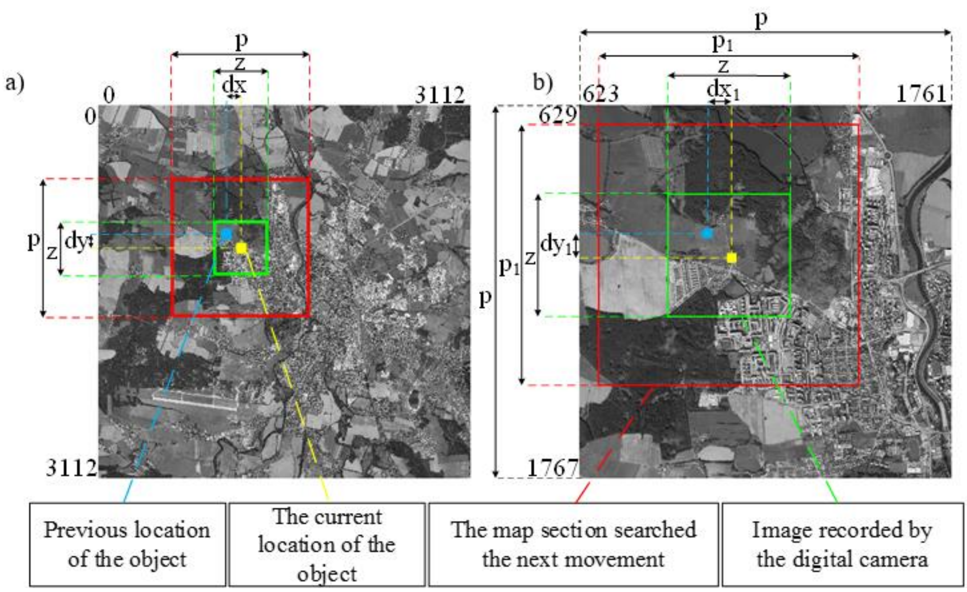

Fig. 6. Dynamic narrowing searching area function: a) search all over the map, b) search a designated portion of a digital map [Grzywacz, 2016]

The registered image is compared with only a fragment of the digital map determined after each subsequent localization of the object on a basis of the following equations [Grzywacz, 2016]:

$$s = \sqrt{dx^2 + dy^2}\ ; \tag{3}$$

$$p = 1.5 \cdot z + 4 \cdot s\ , \tag{4}$$

where:

s — the last movement of the object on the digital map,
p — the size of a digital map fragment searched in the next step,
dx, *dy* — movement of the object along the axis x and y,
z — the size of an image recorded after correction of spatial resolution.

Due to searching only a portion of a digital map, it is necessary to reference coordinates of the designated location of the object to the entire digital map.

Matching of the images is performed using the discrete cross-correlation 2D function described in the following equation [Zieliński, 2005]:

$$R_{xy}(i, j) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} x(m,n)\, y * (m+i, n+j)\,, \tag{5}$$

where:

$x(m,n)$ — image *x* with dimensions m x n,
$y*(m+i,n+j)$ — rotated 180° *y* image with dimensions (*m*+*i*) x (*n*+*j*).

Due to the time-consuming operation above, cross-correlation is conducted in the frequency domain by multiplying arrays of two-dimensional discrete FFT transforms of portion of the digital map and image after rotation and filling by zeros to its size. The resulting product is used to calculate the real part of two-dimensional discrete inverse transform IFFT. The result formed correlation matrix, where searching the maximum value of the matrix, thresholding and binarization allows to indicate the coordinates of the point of maximum matching images. Knowing the size of the image which was being compared and the coordinates of the designated point, it is possible to identify the location of an object on a two-dimensional plane. The location of the object is assumed at the center point of the matched area on a digital map, because it coincides with the mid-point of the observed object through a camera lens. The correlation process shown in Figure 7.

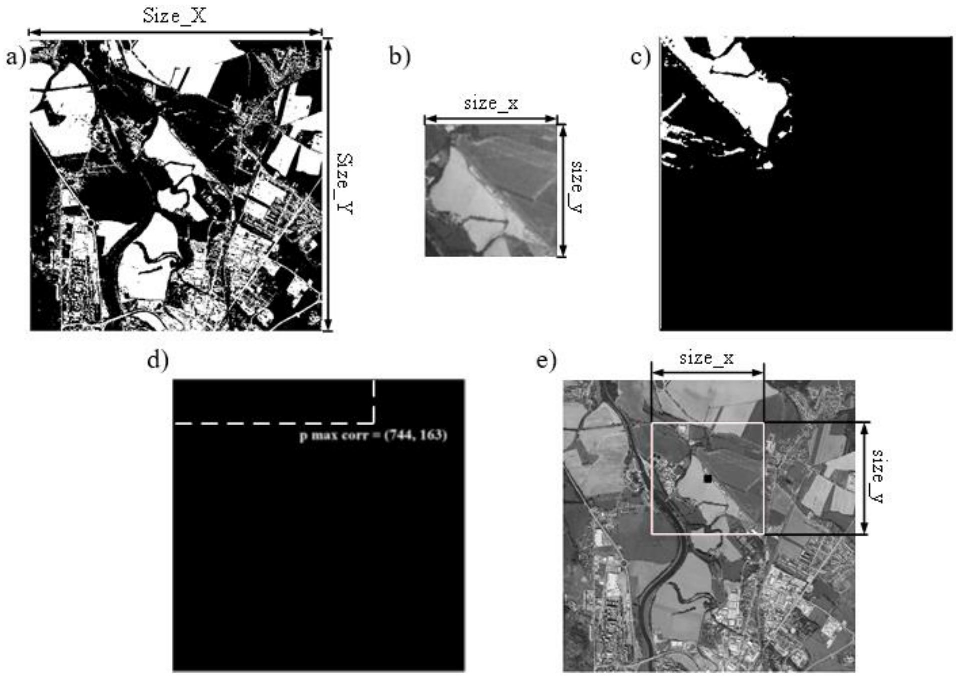

Fig. 7. Stages determine the location of the object in two-dimensional space:
a) a digital map, b) an image captured after preprocessing, c) preparing the image for correlation, d) a binary matrix with point of the maximum correlation extracted, e) matching the processed image to the digital map [Grzywacz, 2016]

STRUCTURE OF THE SYSTEM

Operation of the proposed system is based on the exchange of information between functional blocks, as shown in Figure 8.

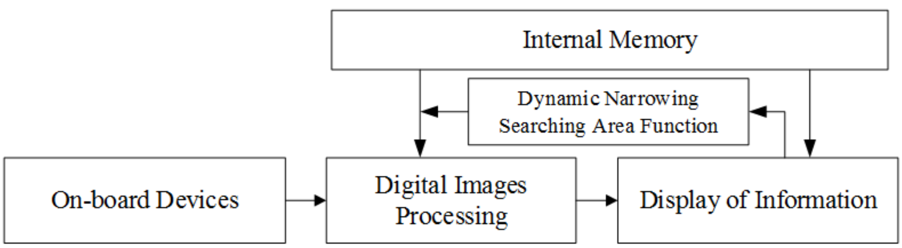

Fig. 8. The block diagram of the proposed navigation system [Grzywacz, 2016]

The internal memory stores data which will remain unchanged for the duration of the flight, i.e. a digital map of the area, the coordinates of the initial location of the object, route waypoints and destination.

The system requires the cooperation of the on-board equipment generating the necessary data:
- on-board recorder — digital image of the area;
- electronic compass — yaw angle of the object;
- altimeter — flight altitude of the object.

In addition, an on-board recorder should be stabilized in pitch and roll angles, to observe the area directly under the air platform. To build the model measurement unit used:
- digital camera Creative Live! Cam Sync HD VF0770 [11] configured to registering an images with resolution 720 x 720 px, communication with PC by USB;
- evaluation board STM32F3Discovery [1] integrated with e-compass/accelerometer MEMS (LSM303DLHC), communication with PC by USB mini-B connector;
- ultrasonic ranging module HC-SR04 [2] used as altimeter to measure distances from 2 to 400 cm range, integrated with the evaluation board.

The block of digital image processing is responsible for designating the location of the object based on the previously discussed operation. The processing steps are depicted in Figure 9.

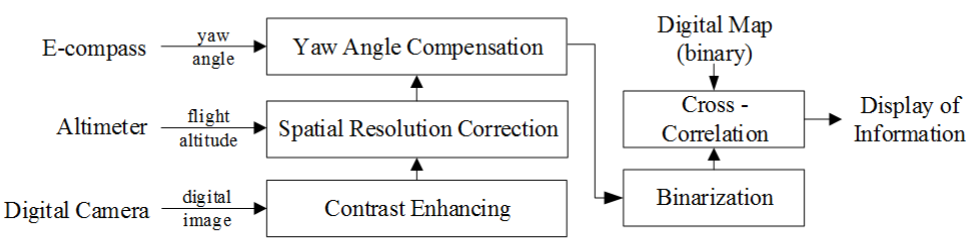

Fig. 9. Stages of image processing [Grzywacz, 2016]

Display of information is carried out by the main application window (Fig. 10), which shows information about the coordinates of the designated location and its graphic interpretation on a digital map. Additionally, the on-board recorder panel enables continuous observation of the area directly under the object, on the sliders the value of the height and yaw angle was shown and the indicator panel informs the navigation azimuth and distance to the nearest waypoint. Pressing *Database* button allows to display the database containing detailed information about the course of the flight: measurement number, location's coordinates, height, yaw angle, processing time, movement distance, velocity, azimuth and distance to the next waypoint.

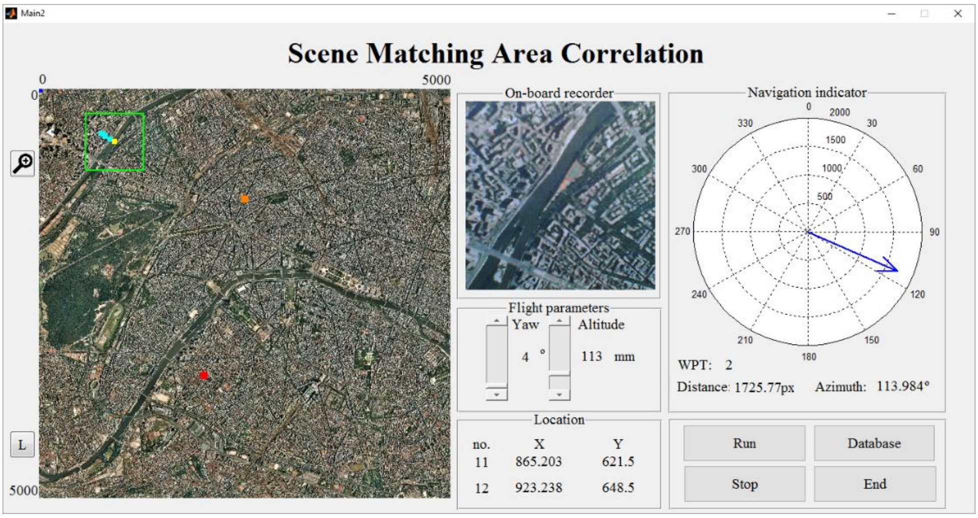

Fig. 10. Computer application [Grzywacz, 2016]

The last element of the structure, i.e. dynamic narrowing searching area function is associated with the transfer of information between the visualization and digital image processing blocks.

ANALYSIS OF THE RESULTS

In order to determine the suitability of cross-correlation function for using in real-time applications, measurement of the time processing of the two images was performed according to their size (Table 2). Measurements were performed in Matlab for two methods of determining the cross-correlation:

- based on the Eq.(5), by the Matlab *xcorr2* method;
- correlation in frequency domain, based on *fft2* and *ifft2* methods.

Tab. 2. Measurement results – the duration of the cross-correlation [Grzywacz, 2016]

Image *x* size	Image *y* size	Processing time [s]	
		Correlation based on the Eq.(5)	Correlation based on *fft* and *ifft*
500	100	0.93	0.05
	500	22.5	0.06
1500	100	7.5	0.42
	500	182.7	0.4
	750	494.91	0.42
5000	100	125.64	6.37
	500	2973.09	6.56
	750	6765.51	6.8

Determination of the correlation matrix *xcorr2*, should not been applicable in real-time applications as it is very time consuming. Correlation in the frequency domain can be performed much faster, which justified the use of this method in the proposed system.

The second study was to check the effect of changes the angle of deviation to the efficiency of the localization in order to determine the accuracy of an information which is required from the on-board device. The study used a total of 50 sectors of two digital maps, as shown in Figure 11, around the marked center points of the observed images. During this test, the yaw angle is not compensated. The results are presented in Table 3 and Figure 12.

a) b)

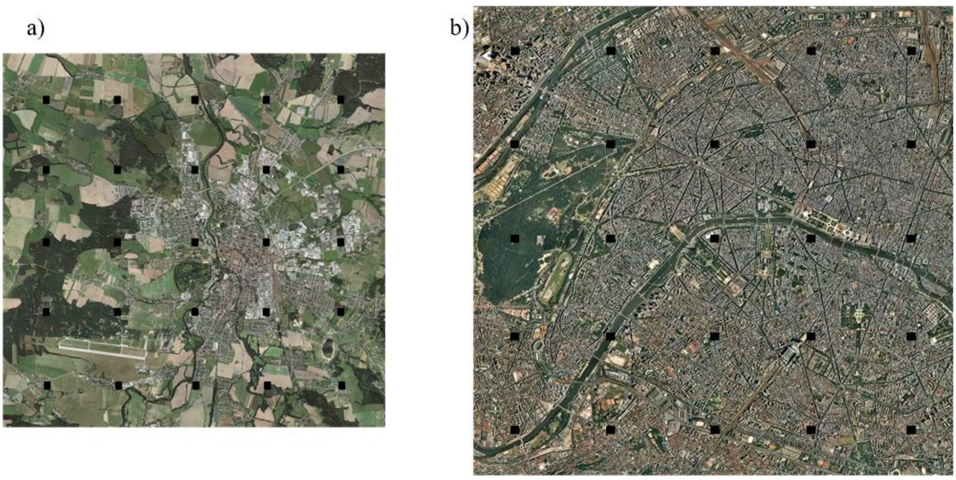

Fig. 11. Digital map: a) map [12] (3112 x 3112 px), b) map [13] (5000 x 5000 px)

Tab. 3. The results of measurements of the localization efficiency as a function of yaw angle

Yaw angle α [°]	Localization efficiency E [%]	Yaw angle α [°]	Localization efficiency E [%]
–1.3	0	0.3	80
–1.2	2	0.4	60
–1.1	2	0.5	46
–1	6	0.6	32
–0.9	8	0.7	18
–0.8	14	0.8	14
–0.7	16	0.9	8
–0.6	28	1	6
–0.5	44	1.1	2
–0.4	60	1.2	2
–0.3	78	1.3	0
–0.2 ÷ 0.2	100		

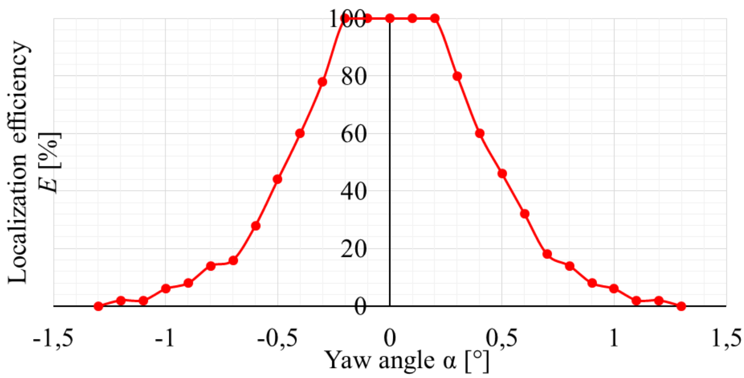

Fig. 12. A graph showing the results of measurements

The test results were used to determine an acceptable range of provided information error about the yaw angle at ± 0.2°. No proper matching of images depending on the angle of deviation is associated with the change position of pixels around a central point in the registered image. This results in the fact that the calculated cross-correlation value for whenever the matching area is changed (suppressing or strengthening, which depends on changes in the image matrix).

Another study was to determine the efficiency of localization depending on the density noise ‘salt and pepper’. For this purpose images from the previous study were used, which have been distorted using a method *imnoise* and subsequently were subjected to a cross-correlation with the corresponding digital map (the case of perfect matching of images). In addition, measurements were performed on images registered with using a measurement station shown in Figure 13 (influence of the devices used and the external conditions).

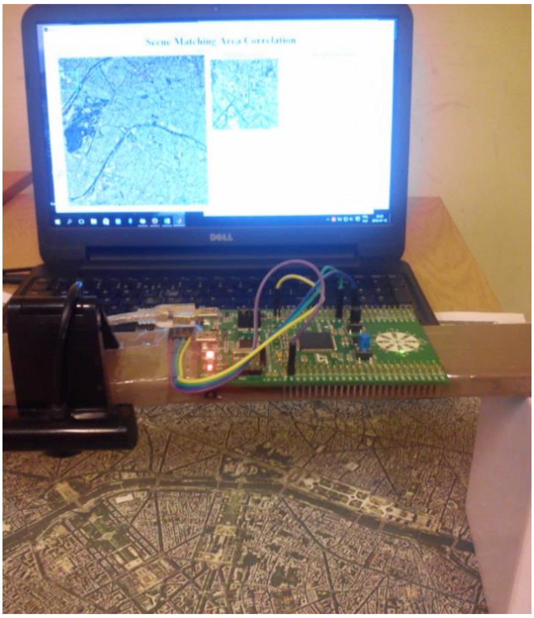

Fig. 13. The measurement station [Grzywacz, 2016]

The measuring station consists of a PC with computer application, discussed earlier model measurement unit and digital map printings [12, 13]. The results of the measurements are shown in Table 4 and Figure 14.

Tab. 4. The results of measurements of the localization efficiency for changes in the noise density

Noise density *d* [%]		0	10	20	30	40	50	60	70	80	90	100
Localization efficiency *E* [%]	Digital map sectors	100	96	94	88	72	68	58	52	48	34	0
	Recorded images	96	92	80	74	58	48	34	22	8	4	0

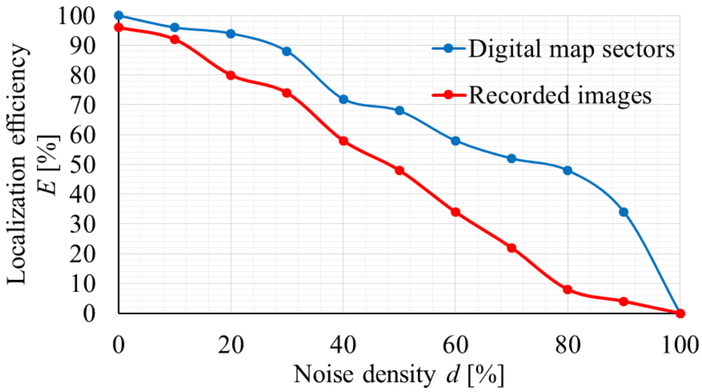

Fig. 14. A graph showing the results of measurements

Depending on the area shown in the digital image obtaining the correct result of the localization was possible despite the noise reaching over 50%. Measurements using the developed measuring unit resulted in getting a slightly lower detection efficiency with increasing noise. This is due to the effect of accumulation of errors related to recorder quality parameters and introduced noise.

The last study shown in the article consisted of measuring the time of processing at the various stages of operation of the proposed system. The complete measurement procedure consists of: processing the image to determine the location of an object, displaying the information, and updating the database. The measurement results are shown in Table 5.

Tab. 5. Results of the measurement time the different stages of the system [Grzywacz, 2016]

Operating stage of the system	Time [s]	Operating frequency [1/min]
Determining of the object localization	0,83	66,67
Display of information	2,84	16,35
Database updating	4,37	7,46

It was noted that the outcome of operating frequencies greatly influenced features that are not necessary in the process of determining the object's location. If the update of the database will only be executed by pressing Database, the frequency of fulfilling the full measurement procedures will increase to 16.35/min, and if you omit the display of information by means of the navigation indicator and digital map this value rises to 66.67/min.

CONCLUSIONS

Obtained results proved the effectiveness of the method when applied to determine the location. Guaranteeing high accuracy to provide information about the angle and height is the basis for correct functioning of the system.

The primary disadvantages of the system are the difficulties in precise localization associated with lack of distinguishing color area features (e.g. the errors above water). In addition, it is required that at the time of image recording, the area be uniformly illuminated.

In the future, the proposed system should be integrated with the INS, and extended to the stabilization of the measurement unit in the pitch and roll angles through the use of a triaxial accelerometer and gyroscope. This will improve mutual properties of the two systems, while maintaining their autonomy.

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STRESZCZENIE

W artykule przedstawiono projekt systemu nawigacji obserwacyjno-porównawczej wykorzystującej kamerę cyfrową, magnetometr oraz impulsowy miernik odległości. Systemy tego typu znajdują zastosowanie jako elementy zaawansowanych zintegrowanych systemów nawigacyjnych, ze względu na swoją autonomiczność i możliwość lokalizacji statków powietrznych z bardzo dużą dokładnością i precyzją. Sterowanie i zobrazowanie realizowane jest przy użyciu aplikacji komputerowej opracowanej w środowisku Matlab. Miejsce położenia obiektu wyznaczane jest za pomocą dyskretnej funkcji korelacji krzyżowej poprzez dopasowanie zarejestrowanego obrazu terenu do wzorca (ortofotomapy cyfrowej). W pierwszej części artykułu opisano operacje bezpośrednio związane z przetwarzaniem obrazów cyfrowych oraz ich zastosowanie dla potrzeb realizowanego projektu. W części drugiej przedstawiono strukturę opracowanego systemu wraz z opisem poszczególnych bloków funkcjonalnych oraz zaprezentowano urządzenia wykorzystane do budowy modelu kompletnej zintegrowanej jednostki pomiarowej. Model wykorzystano do przeprowadzenia pomiarów skuteczności wyznaczania miejsca położenia obiektu w zależności od zmian luminancji, kąta i wysokości lotu oraz poziomu zaszumienia obrazu. Dodatkowo przeprowadzono pomiary częstotliwości pracy systemu w zależności od stopnia rozszerzenia aplikacji o dodatkowe funkcje. Metodyka realizowanych badań została przedstawiona w części końcowej, wraz z analizą uzyskanych wyników, oceną efektywności oraz potencjalnymi kierunkami rozwoju opracowanego systemu.