Multispectral image processing algorithms for enhanced vision systems in the Arctic

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Abstract. The issues of enhanced vision multispectral systems application for robotic complexes control in the Arctic are considered. The existing contrast enhancement methods are observed. Probability characteristics of images being subject to contrast enhancement parameters are estimated. Based on these characteristics, the authors concluded that image areas requiring the greatest contrast enhancement are the areas with low saturation and magnitude gradients, at certain brightness values. Image quality improvement method is proposed. It performs processing only in the areas where it is necessary to enhance the contrast, practically without affecting the most homogeneous or structured image parts. The processed image saturation remains due to the processing of both luminance channel and saturation channel. The algorithm proposed also provides contrast enhancement of shaded image areas. The calculated values of various objective image quality indices indicate that the contrast enhancement algorithm proposed provides better results than known approaches. In addition, different spectral range image fusion algorithm ensuring visibility in the presence of interfering factors is proposed. It differs from known methods by adaptive weight adjustment in different areas of image. The example confirming the effectiveness of the fusion method proposed is shown. For its comparison with known methods, the values of fusion objective quality indices are calculated. The fusion algorithm proposed is shown to surpass known methods by various quality assessments. The conclusion about the expediency of using the algorithms developed in technical vision systems of robotic complexes in the Arctic is made.

1. Introduction
To ensure the visibility in the conditions of arduous Arctic weather, to control remotely ground-based robotic complexes (RC) effectively, it is appropriate to use multi-range enhanced vision systems. These systems perform operation of integrating source video stream images into a single image, containing information about every object distinguishable in the image of at least one channel, as well as the stage of image quality enhancement, involving contrast and sharpness enhancement, brightness correction, and front plan moving snowflakes elimination. This approach allows combining the advantages of using multispectral sensors and significantly improving visibility in low light conditions and the presence of some interfering factors, such as snow or fog [1].

2. Proposed contrast enhancement algorithm
During image acquisition in the Arctic, there may be adverse weather conditions, such as snowflakes, fog, smoke or smog. The action of these phenomena leads to the decrease in image quality leading to
contrast decrease and visibility deterioration. This causes difficulties of object detection and recognition, which can lead to serious errors in the process of RC remote control. Thus, it is advisable to use contrast increase algorithm allowing to improve the quality of images in the enhanced vision block.

In works [2,3,4] the well-known variants of adaptive equalization histogram with restriction (CLAHE) algorithm, being one of the most common methods to increase contrast, are described. Within the framework of this algorithm, level restriction and alignment of brightness histograms of rectangular image fragment pixels is carried out, which leads to the expansion of the dynamic range of brightness values and, consequently, to contrast increase [5]. The disadvantages of the algorithms described include image lightening, saturation lowering, the appearance of “halos” near object borders as well as the manifestation of noise and compression artifacts in the most homogeneous areas of algorithm [3].

The task to develop a contrast improvement algorithm eliminating the drawbacks of known approaches while maintaining the required degree of contrast enhancement seems very important.

The developed algorithm proposes a new way to isolate “problem” image areas exposed to fog, precipitation, smoke, etc. Using such approach the algorithm focuses only in those areas where it is necessary to increase contrast without affecting the most homogeneous and structured areas of an image. This contributes to significantly less distortion, such as noise, "halo", clarification, etc., compared with known algorithms.

The proposed method of identifying "problem" regions is based on the analysis of information about average values of brightness \( I_{cp} \), saturation \( S_{cp} \) and magnitude of gradients \( M_m \) of image areas. This information is necessary for calculating auxiliary parameters being further used to calculate full parameter of brightness pixel histograms limitation, and hence the degree of contrast enhancement in each image block. The use in the developed approach of average gradient magnitude rather than the dispersion of the rectangular block used in algorithm [4], is explained by a more accurate description of structuring (or homogeneity) of image area in a gradient magnitude map. The calculation of this map is carried out with the help of the Sobel operator [5,6].

To determine the type of dependences of contrast enhancement level on image characteristics used, probabilistic distributions \( p(I) \), \( p(S) \), \( p(M) \) and brightness \( I \), saturation \( S \) and magnitudes of gradients \( M \) values of fragments exposed to hydrometeors and smoke were constructed. The constructed distribution histograms as well as the dependencies used to describe them in the developed algorithm are shown in Figure 1.

From the analysis of the distributions presented, it can be concluded that the most “problematic” parts of the image, which require the greatest increase in contrast, correspond to areas with low, but not minimal values of saturation and magnitude of gradients, at brightness values slightly above average.
To describe probability characteristics $p(I)$ the developed algorithm proposes to use the mixture of two beta distributions with different parameters $\alpha$, then dependence $z_i(I_m)$ will take the form:

$$z_i(I_m) = f_{\beta_1}(I_m) + f_{\beta_2}(I_m),$$

(1)
where \( f_{\beta_1}(I_m) \) and \( f_{\beta_2}(I_m) \) are probability density functions (PDF) of beta distributions (Figure 1, b). The description of characteristic \( p(S) \) is proposed to be carried out using a mixture of beta and normal distributions

\[
z_2(S_m) = f_{\beta}(S_m) + f_N(S_m), \tag{2}
\]

where \( f_{\beta}(S_m) \) and \( f_N(S_m) \) are PDFs of beta and normal distributions, respectively (Figure 1, d).

According to preliminary experimental studies, high accuracy requirements are imposed on the description of probabilistic characteristic \( p(M) \) due to the difficulty of separating the classes of image fragments exposed to hydrometeors or smoke from the class of the most homogeneous areas such as the sky. Therefore, to describe this characteristic, it is advisable to use not a mixture of distributions, but a piecewise specified function of the form

\[
z_3(M_m) = \begin{cases} 
F_{Ln}(M_m), & M_m \leq 0.03, \\
F_{E}(M_m), & M_m > 0.03, 
\end{cases} \tag{3}
\]

where \( F_{Ln}(M_m) \) is the integral function of lognormal distribution, \( F_{E}(M_m) \) is PDF of exponential distribution (Figure 1, e).

Distributions \( p(I) \), \( p(S) \) and \( p(M) \) are obtained for fragments of images with poor visibility, therefore, in order to be able to slightly improve the contrast of foreground objects, which are less affected by fog, the dependencies \( z_1(I_m) \), \( z_2(S_m) \) and \( z_3(M_m) \) do not exactly coincide with these distributions at small PDFs.

The auxiliary parameter \( z_{12} \) is a function of two variables \( I_m \) and \( S_m \) being calculated by the formula

\[
z_{12}(I_m, S_m) = \sqrt{z_1(I_m) \cdot z_2(S_m)}. \tag{4}
\]

Also, the algorithm proposed provides the improving of contrast in shaded and darkened areas of a television image which is achieved using the dimming parameter \( z_d(I_m, S_m) \), which is a function of two variables, the maximum of which is located in the region of low brightness values and high saturation values.

Full parameter \( \gamma_0 \) of histogram restriction is calculated by the formula

\[
\gamma_0 = z_3(M_m) \cdot z_{12}(I_m, S_m) + z_d(I_m, S_m). \tag{5}
\]

Another feature of the algorithm proposed is the not only luminance channel processing carried out in well-known variants of the CLAHE algorithm, but also the processing of the channel responsible for transmitting color information saturation. Such processing ensures the preservation of processed image saturation.

The algorithm developed contains the following steps:

- source image is converted to HSI color space where saturation information \( S \) is separated from colour tone information \( H \), which allows channel \( S \) to be processed without affecting component \( H \), unlike YCbCr model, which is used in the known algorithms considered;
- image separation of lightness \( I \) and saturation \( S \) channels into rectangular blocks and construction of pixel value histograms for each block is implemented;
- characteristics of each image fragment, such as average values of brightness, saturation and magnitude of gradients are calculated;
- values of auxiliary parameters are determined according to dependencies (1–3), and then, using formula (5), full parameter \( \gamma_0 \) of histogram limitation, which shows the degree of contrast increase is determined;
histograms are limited, “cropped” pixels are redistributed and histograms are aligned in the same way as well-known CLAHE [2,3,4] variants; however, if in these options these transformations are performed only for brightness channel, in the algorithm proposed they are also performed for saturation components;

processed components $I$ and $S$ are merged with source component $H$ and resulting image is converted into an RGB color model;

Gamma correction is applied to eliminate lightening effect.

3. Multispectral image fusion algorithm

The overview of multispectral image fusion methods is given in [7]. One of the approaches ensuring a relatively high value of fusion quality index [8] is weight summation with information content assessment [7].

According to this algorithm, equal weights $s_1$ and $s_2$, are applied to all $I_1$ and $I_2$ image pixels, respectively. The basic principle of the algorithm proposed is various channel images weight summation with individual values of normalized weights $s_1(x,y)$ and $s_2(x,y)$ for each pixel with coordinates $(x,y)$.

$$I_c(x,y) = s_1(x,y)I_1(x,y) + s_2(x,y)I_2(x,y).$$

At the first stage of the proposed fusion algorithm, the images are divided into intersecting square fragments $U_{i,j}$ and $V_{i,j}$, with side length $W_s$ pixels. For image $u$:

$$U_{i,j}(x_u,y_u) = u(x,y),$$

where $x = (i-1)W + 1, (i+1)W + 1$, $y = (j-1)W + 1, (j+1)W + 1$; $x_u$, $y_u$ are pixel coordinates inside the fragment, $i = \lfloor\frac{2X}{W_s}\rfloor$, $j = \lfloor\frac{2Y}{W_s}\rfloor$ are indices defining the position of the fragment horizontally and vertically, respectively; brackets \(\lfloor\cdot\rfloor\) mean extracting the integer part of the number, $W = (W_s - 1)/2$. Window size $W_s$ is odd.

Next, for each fragment $U_{i,j}$, the value of standard deviation of central pixel value is determined by formula:

$$u_{i,j} = \frac{1}{W_s^2} \left( \sum_{x_w=1}^{W_s} \sum_{y_w=1}^{W_s} \left( U_{i,j}(x_w,y_w) - U_{i,j}(W+1,W+1) \right)^2 \right)^{1/2}. $$

Similarly, fragments $V_{i,j}$ are selected on image $v$ and values $v_{i,j}$ are determined.

To assess information content of multispectral images fragments, angles $\varphi_{i,j}$ are calculated:

$$\varphi_{i,j} = \arctg \left( \frac{u_{i,j}}{v_{i,j}} \right).$$

Angle map $\varphi_{i,j}$ must be transformed to original images $u$ and $v$ resolution. Classical interpolation methods, such as stepwise, bilinear and bicubic interpolation do not provide sufficient smoothing of high-resolution angle map values. Therefore, the transition to a new array size of angles $\varphi(x,y)$ is made according to formula:

$$\varphi(x,y) = \sum_{i=1}^{\lfloor\frac{2X}{W_s}\rfloor} \sum_{j=1}^{\lfloor\frac{2Y}{W_s}\rfloor} \varphi_{i,j} K(x_G + iW + 1, y_G + jW + 1),$$

where $x_G = \lfloor x \rfloor, y_G = \lfloor y \rfloor$ are integer parts of $x$ and $y$.
where \( K(x_G, y_G) = \exp\left(-\frac{x_G^2 + y_G^2}{2\sigma^2}\right) \) — two-directional Gaussian window with parameter \( \sigma = W / 6 \), \( x_G, y_G = \pm W, W \).

After map \( \phi(x, y) \) is determined, a resulting image is calculated as follows:

\[
c(x, y) = u(x, y) \cos \phi(x, y) + v(x, y) \sin \phi(x, y).
\]

(11)

### 4. Results of offered algorithm application

To obtain the objective quality assessment of a proposed image contrast enhancement algorithm the original version of CLAHE algorithm \([2,3]\) was compared with its well-known modification \([4]\) using the following processed images quality indices (QI): mean square error (MSE), structural similarity index (SSIM) \([9]\), quality of edges (QE) \([10]\), feature mutual information with gradient feature extraction (Fast-FMI) \([11]\). Three types of images from \([12]\) database were used to calculate QIs: reference image (without hydrometeors or smoke interference), fogged image (reference image with simulated fog) and processed image. QIs were calculated for different scenes and then averaged. QI values of images processed by the algorithms compared are presented in Table 1.

| Algorithm                  | MSE    | SSIM   | QE     | Fast-FMI |
|----------------------------|--------|--------|--------|----------|
| Initial CLAHE \([2,3]\)    | 0.0526 | 0.702  | 0.3636 | 0.581    |
| Known modification of CLAHE \([4]\) | 0.0546 | 0.7157 | 0.4043 | 0.5793   |
| Proposed algorithm         | 0.0438 | 0.8279 | 0.7160 | 0.6024   |

According to the data from Table 1, a proposed contrast enhancement algorithm provides, on average, the best QIs of the images processed compared to known approaches. For example, superiority in QE and SSIM is 77 ... 97% and 16 ... 18%, respectively, and root-mean-square error decreased by 17 ... 20% in comparison with known algorithms.

The contrast enhancement algorithm developed provides the best results as compared with known methods also by real images processing. So, while maintaining contrast enhancement degree, the images processed by the algorithm proposed look more natural and practically do not contain distortions of brightness and saturation, as well as noise and halos, the appearance of which is inherent in known considered approaches.

In Figure 2, the examples of source images as well as proposed and three well-known fusion algorithms are shown. Here the letters correspond to: \( a \) is an original SWIR image, \( b \) is a thermal LWIR image, \( c \) corresponds to a proposed algorithm, \( d \) is result of informativeness assessment algorithm using result \([7]\), \( d \) corresponds to the selection of local contrasts \([7]\) and \( e \) – 3D LPF \([13]\).
Figure 2. Examples of using the results of various multispectral image fusion algorithms

For objective result comparison, fusion quality assessments by three QIs were calculated: FAST-FMI with gradient extraction [11], QE [10], SSIM modification [14]. These values are shown in Table 2.

| Fusion method                              | FAST-FMI | QE   | SSIM |
|--------------------------------------------|----------|------|------|
| Proposed algorithm                         | 0.459    | 0.732| 0.943|
| Evaluation of informativeness [7]          | 0.315    | 0.347| 0.642|
| Selection of local contrasts [7]           | 0.391    | 0.546| 0.779|
| 3D LPF [13]                                | 0.232    | 0.312| 0.549|

Analysis of this table shows that the proposed fusion algorithm surpasses the known methods by at least 0.068 units in FAST-FMI; 0.186 units in QE and 0.164 in SSIM.

5. Conclusion

In this paper, the distributions of some characteristics (brightness, saturation, magnitude of gradients) of image fragments containing fog or smoke is shown. A contrast enhancement algorithm using the shown characteristics for automatic adjustment of contrast and saturation enhancement degree in certain image parts is proposed. The proposed algorithm provides processed image QI gain in comparison with the known considered approaches. For example, QE presents two times gain.

In addition, a multispectral image fusion algorithm, which provides automatic weighting coefficient calculation in various areas of original frames is proposed. The example confirming the effectiveness of the algorithm presented is shown. According to the calculated values of objective quality indices FAST-FMI, QE and SSIM, the algorithm proposed surpasses known multispectral image fusion methods.

The results obtained show the feasibility of applying proposed algorithms in robotic complexes multispectral vision systems in the Arctic.
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