Method of transmission of dynamic multibit digital images from micro-unmanned aerial vehicles

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Abstract. In connection with successful usage of nanotechnologies in remote sensing great attention is paid to the systems in micro-unmanned aerial vehicles (MUAVs) capable to provide high spatial resolution of dynamic multibit digital images (MDI). Limited energy resources on board the MUAV do not allow transferring a large amount of video information in the shortest possible time. It keeps back the broad development of MUAV. The search for methods to shorten the transmission time of dynamic MDIs from MUAV over the radio channel leads to the methods of MDI compression without computational operations onboard the MUAV. The known compression codecs of video information can not be applied because of the limited energy resources. In this paper we propose a method for reducing the transmission time of dynamic MDIs without computational operations and distortions onboard the MUAV. To develop the method a mathematical apparatus of the theory of conditional Markov processes with discrete arguments was used. On its basis a mathematical model for the transformation of the MDI represented by binary images (BI) in the MDI, consisting of groups of neighboring BIs (GBI) transmitted by multiphase (MP) signals, is constructed. The algorithm for multidimensional nonlinear filtering of MP signals is synthesized, realizing the statistical redundancy of the MDI to compensate for the noise stability losses caused by the use of MP signals.

1. Introduction

Due to the progress in the development of unmanned aerial vehicles on small platforms and the development of means for obtaining multibit digital images (MDI) of high spatial resolution, the creation of remote sensing on micro unmanned aerial vehicles (MUAV) is of great interest. According to experts, 50 percent of useful video information in near real-time mode is obtained from the MUAV at the operational level [1]. A significant disadvantage of MUAV is the "tight" restrictions on energy resources, therefore one of the actual tasks to be solved when creating an MUAV is the minimization of energy resources onboard of the MUAV for the transfer of dynamic MDI in the shortest possible time.

The search for methods to reduce the transmission time of dynamic high-resolution MDI has led to the development of methods for compressing dynamic MDIs without computational operations that are not critical to the resolution of dynamic MDIs, which exceed the known video compression methods, such as MPEG2, MPEG4 [2,3]. These codecs require the implementation of large time and energy resources, so they can not be implemented onboard the MUAV. Therefore, the development of new methods and improvement of the known ones for reducing the time of transfer of originals of dynamic MDIs without distortion and computational operations onboard the MUAV is urgent.
2. Description of Method

The paper suggests a method for solving the problem to reduce the transmission time of dynamic MDI from the MUAV board. The method consists of two parts. The first part consists in the transformation of the originals of dynamic MDI, consisting of binary images (BI) (Figure 1) in the MDI, consisting of groups of neighboring BIs (GBIs) comprising two or more BIs (Figure 2) obtained onboard the MUAV.

![Figure 1. An example of dividing a dynamic MDI frame into a BI](image1)

The number of GBIs is smaller than the BI, the transition from BI to GBI is carried out in every MDI without distortion and computational operations on board of the MUAV, which allows to reduce the time of transfer of dynamic MDI without the cost of energy resources onboard of the MUAV. For the transmission of GBI via the radio channel, multiphase manipulated (MP) signals are used. It is possible to use other types of signals, for example, multifrequency (MF) signals as well.

A significant drawback of the use of MP signals for the transmission of dynamic MDI, consisting of BI, is the noise immunity of receiving MP signals by 3 dB in power for each division of the phase of the MP signal by 2. For example, in the transition from MP signals with two phase states to MP signals with four phase states, the transmission time and interference immunity of reception of MDI, consisting of BI, is reduced by half.

![Figure 2. The combination of two BIs in GBIs](image2)

The second part, more complicated, consists in developing a method for realizing the statistical redundancy of originals of dynamic MDIs to improve the interference stability of MP signals receiving sufficient to compensate for the loss of noise stability caused by the use of MP signals for the transmission of dynamic MDIs.

Based on the representation of the transformed dynamic MDIs by three-dimensional Markov processes with discrete arguments with several (more than two) states and the theory of
multidimensional nonlinear filtration, there have been developed a mathematical model of dynamic MDI consisting of BI with two or more BIs and an algorithm for three-dimensional nonlinear filtering of the transformed dynamic MDI transmitted MP signals, effectively realizing the statistical redundancy of the originals of dynamic MDIs for improving the noise stability of receiving MP signals. It allowed to reduce the transmission time of dynamic MDI by several times without the loss of noise stability and without the cost of energy resources onboard the MUAV.

We will assume that in each frame of the BI \( g \) BIs is combined and the dynamic MDI is approximated by three-dimensional Markov processes with discrete arguments with several states \( N = 2^k \) with the probability vector of the initial states \( P = \{p_1, p_2, \ldots, p_N\}^T \) and the transition probability matrix (MTP) \( ^1\Pi, ^2\Pi \) and \( ^4\Pi \) from the state \( M_i \) to the neighboring state \( M_j \) \((i, j \in N)\) along the horizontal, vertical and between frames, respectively [4]:

\[
^1\Pi = \begin{pmatrix}
\pi_{11} & \pi_{12} & \cdots & \pi_{1N} \\
\pi_{21} & \pi_{22} & \cdots & \pi_{2N} \\
\cdots & \cdots & \cdots & \cdots \\
\pi_{N1} & \pi_{N2} & \cdots & \pi_{NN}
\end{pmatrix},
^2\Pi = \begin{pmatrix}
\pi_{11} & \pi_{12} & \cdots & \pi_{1N} \\
\pi_{21} & \pi_{22} & \cdots & \pi_{2N} \\
\cdots & \cdots & \cdots & \cdots \\
\pi_{N1} & \pi_{N2} & \cdots & \pi_{NN}
\end{pmatrix},
^4\Pi = \begin{pmatrix}
\pi_{11} & \pi_{12} & \cdots & \pi_{1N} \\
\pi_{21} & \pi_{22} & \cdots & \pi_{2N} \\
\cdots & \cdots & \cdots & \cdots \\
\pi_{N1} & \pi_{N2} & \cdots & \pi_{NN}
\end{pmatrix}.
\] (1)

The mathematical model of dynamic BI is presented in figure 3.
The state of the element $v_4$ depends only on the known elements of a certain subset $\Lambda_{i,j,k}$, called the neighborhood of the element. The best way to satisfy the condition of causality is the configuration of the neighborhood (Figure 4)

$$\Lambda_{i,j,k} = \{v_1, v_2, v_3, v'_1, v'_2, v'_3, v_4\}$$  \hfill (2)

The transition probabilities from the states of the elements $\Lambda_{i,j,k}$ to the state $v_4$ form a MTP of the form [4]:

$$\Pi = \begin{bmatrix}
\pi_{i1} & \pi_{i2} & \cdots & \pi_{iN1} \\
\pi_{i2} & \pi_{i3} & \cdots & \pi_{iN2} \\
\vdots & \vdots & \ddots & \vdots \\
\pi_{iN1} & \pi_{iN2} & \cdots & \pi_{iNN}
\end{bmatrix}, \quad i, j, k, l = 1, N$$  \hfill (3)

With known matrices $\Pi_1, \Pi_2, \Pi_3$ to calculate the elements of the matrix $\Pi$ (3), it is necessary to first calculate the matrices

$$\begin{align}
3\Pi &= \Pi_1 \cdot 2\Pi; & 5\Pi &= \Pi_1 \cdot 4\Pi; & 6\Pi &= 2\Pi \cdot 4\Pi; \\
7\Pi &= 3\Pi \cdot 4\Pi &= 1\Pi \cdot 2\Pi \cdot 4\Pi.
\end{align}$$  \hfill (4)

which define statistical relationships between the elements of the neighborhood $\Lambda_{i,j,k}$ with element $v_4$.

The values of the elements of the matrix $\Pi$ (4) can be calculated as follows:

$$\pi_{i1} = \frac{1}{2} \frac{\pi_{y_1} \cdot 2 \pi_{y_2} \cdot 4 \pi_{y_3} \cdot 7 \pi_{y_4}}{\pi_{u_1} \cdot \pi_{u_2} \cdot \pi_{u_3} \cdot \pi_{u_4}}, \quad \pi_{i2} = \frac{1}{2} \frac{\pi_{y_1} \cdot 2 \pi_{y_2} \cdot 4 \pi_{y_3} \cdot 7 \pi_{y_4}}{\pi_{u_1} \cdot \pi_{u_2} \cdot \pi_{u_3} \cdot \pi_{u_4}}, \quad \cdots,$$

$$\pi_{iN1} = \frac{1}{2} \frac{\pi_{y_1} \cdot 2 \pi_{y_2} \cdot 4 \pi_{y_3} \cdot 7 \pi_{y_4}}{\pi_{u_1} \cdot \pi_{u_2} \cdot \pi_{u_3} \cdot \pi_{u_4}}, \quad \cdots, \quad \pi_{iN2} = \frac{1}{2} \frac{\pi_{y_1} \cdot 2 \pi_{y_2} \cdot 4 \pi_{y_3} \cdot 7 \pi_{y_4}}{\pi_{u_1} \cdot \pi_{u_2} \cdot \pi_{u_3} \cdot \pi_{u_4}},$$

$$\pi_{iN1} = \frac{1}{2} \frac{\pi_{y_1} \cdot 2 \pi_{y_2} \cdot 4 \pi_{y_3} \cdot 7 \pi_{y_4}}{\pi_{u_1} \cdot \pi_{u_2} \cdot \pi_{u_3} \cdot \pi_{u_4}}, \quad \cdots, \quad \pi_{iNN} = \frac{1}{2} \frac{\pi_{y_1} \cdot 2 \pi_{y_2} \cdot 4 \pi_{y_3} \cdot 7 \pi_{y_4}}{\pi_{u_1} \cdot \pi_{u_2} \cdot \pi_{u_3} \cdot \pi_{u_4}}.$$

The expressions for calculating the elements of the first row of the matrix $\Pi$ are given. The calculation of the remaining matrix elements for various combinations of pixel values of the neighborhood $\Lambda_{i,j,k}$ is carried out in a similar way.

**The algorithm for multidimensional nonlinear filtering of BI from g BI**
The system of equations for multidimensional nonlinear filtering of dynamic MDI, consisting of BI with g BI, transmitted by MP signals, can be represented in the form [5-7]:

\[
\begin{align*}
\dot{u}_{1i(k)}(v_4) &= \left[ f(M_1(v_4)) - f(M_0(v_4)) \right] + u_{1i(k)}(v_4) + z_i(u(v_i), \pi_y) + \\
&\quad + u_{1i(k)}(v_2) + z_i(u(v_2), \pi_y) + u_{1i(k)}(v_3) + z_i(u(v_3), \pi_y) + \\
&\quad - u_{1i(k)}(v_4) - z_i(u(v_4), \pi_y) - u_{1i(k)}(v_4) - z_i(u(v_4), \pi_y) - u_{1i(k)}(v_4) - z_i(u(v_4), \pi_y),
\end{align*}
\]

\[
\begin{align*}
\dot{u}_{2i(k)}(v_4) &= \left[ f(M_2(v_4)) - f(M_0(v_4)) \right] + u_{2i(k)}(v_4) + z_i(u(v_i), \pi_y) + \\
&\quad + u_{2i(k)}(v_2) + z_i(u(v_2), \pi_y) + u_{2i(k)}(v_3) + z_i(u(v_3), \pi_y) + \\
&\quad - u_{2i(k)}(v_4) - z_i(u(v_4), \pi_y) - u_{2i(k)}(v_4) - z_i(u(v_4), \pi_y) - u_{2i(k)}(v_4) - z_i(u(v_4), \pi_y),
\end{align*}
\]

\[
\begin{align*}
\dot{u}_{(N-1)i(k)}(v_4) &= \left[ f(M_{N-1}(v_4)) - f(M_0(v_4)) \right] + u_{(N-1)i(k)}(v_4) + z_i(u(v_i), \pi_y) + \\
&\quad + u_{(N-1)i(k)}(v_2) + z_i(u(v_2), \pi_y) + u_{(N-1)i(k)}(v_3) + z_i(u(v_3), \pi_y) + \\
&\quad - u_{(N-1)i(k)}(v_4) - z_i(u(v_4), \pi_y) - u_{(N-1)i(k)}(v_4) - z_i(u(v_4), \pi_y) - u_{(N-1)i(k)}(v_4) - z_i(u(v_4), \pi_y),
\end{align*}
\]

where \( u_j(v_4) = \ln \left[ \frac{p_j(v_4)}{p_N(v_4)} \right] \) (\( j = \overline{1,N} \)), \( p_j(v_4) \) (\( j = \overline{1,N} \)) is a posteriori probability of the state of the discrete parameter of the IMF signal in the pixel \( v_4 \) MM GBI (Fig. 4), \( f(M_j(v_4)) - f(M_N(v_4)) \) (\( j = \overline{1,N} \)) is the difference between the logarithms of the likelihood function of the states of the discrete parameter of the MP signal in the GBI pixel; \( z_j(\cdot) \) is a nonlinear function of the form:

\[
z_j(u(v_i), \pi_y) = \ln \left[ \frac{\sum_{i=1}^{N-1} \exp(u_i(v_i) - u_j(v_i), \pi_y) + \exp(-u_j(v_i), \pi_y) + \pi_y)}{\sum_{i=1}^{N-1} \exp(u_i(v_i), \pi_y) + \pi_y) + \pi_y} \right], \quad (q = \overline{1,N-1}, l = \overline{1,7})
\]

As a criterion for distinguishing the states of the elements of the CBI, we take the criterion of the maximum of the logarithm of the ratio of a posteriori probabilities, \( u_j(v_4) \), in accordance with which, if \( u_j(v_4) > u_i(v_4) \), \( i, j = \overline{1,N-1}; i \neq j \), then a decision is taken on the state of the image element \( v_4 = M_j \); if all values \( u_j(v_4) \leq 0 \) (\( j = \overline{1,N-1} \)), then a decision is taken on the state of the image element \( v_4 = M_N \).

3. Experimental results
To demonstrate the proposed method we simulated the process of transmission and reconstruction of the dynamic MDI, consisting of BI with \( g = 4 \) BI at a signal-to-noise ratio of the signal power at the input of the non-linear filter of 0 dB. The pictures show a frame of a dynamic MDI represented by a set of two GBIs, each of which includes four neighboring BIs (Figure 5), distorted (Figure 6) and a reconstructed NDI frame (Figure 7). Fig. 8 and 9 show the distorted and reconstructed frame of the dynamic MDI with a signal-to-noise ratio at the input of the non-linear filter of 3 dB. To assess the quality of nonlinear filtering of dynamic MDI, the standard error MSE was taken.
Figure 5. Dynamic MDI frame onboard of the MUAV

Figure 6. Dynamic MDI frame at the input of the receiver, MSE = $37 \times 10^2$

Figure 7. Recovered frame of dynamic MDI, MSE = $2,75 \times 10^2$
Figure 8. Dynamic MDI frame at the input of the receiver, MSE = 15.9×10^2

Figure 9. Reconstructed frame of dynamic ISC, MSE = 0.73×10^2

4. Conclusions
The analysis of the results shows that, despite the decrease in noise immunity arising due to the use of MP signals, the losses in noise immunity are completely compensated by the statistical redundancy of the MDI. The transmission time was reduced by a factor of four compared to the direct transmission of MDI by binary signals. Losses in noise stability of reception of MDI, consisting of GBIs, are completely compensated by the implementation of statistical redundancy of MDI.

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