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Analyzing Natural Pixel Color Variations in Consecutive Video Frames to Enhance Spatial Domain Video Steganography*

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Abstract

This study focuses on spatial domain video steganography, motivated by the increasing need for secure data embedding methods that leverage natural video properties to remain undetectable. Existing literature has largely overlooked the detailed statistical characterization of naturally occurring pixel color differences across consecutive video frames. This gap hinders the development of encoding techniques that effectively exploit these variations to enhance the imperceptibility of hidden data. To address this void, the study analyzes the statistical properties of pixel color differences in video frames, examining histograms and frequency patterns to identify predictable natural variations. Using a diverse sample of video files, the analysis revealed distinct patterns in color changes, which are crucial for understanding how to embed data seamlessly within the inherent noise of video content. The findings contribute both theoretically and practically: theoretically, by offering a deeper understanding of the statistical behavior of pixel color differences, and practically, by providing a framework to inform and guide the development of advanced spatial domain steganographic methods. These methods aim to exploit natural noise to reduce detectability while maintaining video quality. This work lays the foundation for further research into resilient and imperceptible steganographic techniques, addressing a critical need in secure data communication.

Keywords: steganography, video steganography, video noise, information encoding

Introduction

Steganography, a sophisticated and well-established field within the domain of information theory, introduced by Shannon (1948) focuses on the development and systematic analysis of techniques that allow the embedding of information within seemingly innocuous covers (Kahn, 1967). The core objective of this discipline is to facilitate covert communication, ensuring that unauthorized parties remain oblivious to the presence of hidden data. By doing so, steganography safeguards the confidentiality and integrity of information across applications ranging from secure messaging and digital watermarking to copyright protection and data integrity verification (Johnson, et. al., 1998).

Over the decades, researchers have proposed and refined a diverse array of steganographic techniques (Johnson, et. al., 2001), each distinguished by its unique methods and applications. The central principle across these techniques is to embed information within a digital cover medium - be it a text file, digital image, audio stream, video sequence, or even network transmission - so that the resulting steganogram closely mimics the original cover (Sencar, et al., 2004). This meticulous engineering ensures that the hidden message remains undetectable, making detection by unauthorized observers challenging or practically infeasible (Petitcolas, et al., 1999). Selecting an appropriate steganographic technique requires consideration of various factors, including the nature

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of the cover medium and the desired attributes of the method, such as capacity, robustness, and undetectability (Fridrich, 2009).

In the specialized domain of image (Cox, et al., 2007; Kadhim, et al., 2019) and video steganography (Sadek, et al., 2014), two primary approaches have emerged: spatial domain steganography and transform domain (or frequency domain) steganography (Katzenbeisser, et al., 2000). Spatial domain techniques operate by directly manipulating pixel values - such as color, brightness, or contrast - within an image or video frame (Chan, et al., 2004). These methods are relatively straightforward to implement and can accommodate various forms of data, but they may be more susceptible to detection and distortion, particularly under methods of steganalysis. Conversely, transform domain techniques involve converting the cover medium into the frequency domain through processes like Discrete Cosine Transform (DCT) or Discrete Wavelet Transform (DWT) (Chang, et al., 2002). Modifying the coefficients in this domain allows for more robust embedding, often rendering the hidden data less susceptible to compression or other distortions. Each approach has its strengths and limitations, with the optimal choice largely dependent on specific use cases, transmission environments, and potential processing challenges (Anderson, et al., 1998).

This study centers on elucidating the principles underpinning video steganography techniques that leverage spatial domain encoding algorithms. These methods modify pixel color values in consecutive video frames, encoding information bit by bit in a manner designed to blend seamlessly with the inherent visual properties of the content. However, such modifications must remain indistinguishable from the natural noise present in video files, which can arise from several sources (Kunhoth, et al., 2023, including:

- inter-frame transitions - variations in pixel values between frames that create the perception of motion,
- compression artifacts - distortions introduced by video codecs (e.g., H.264, H.265) through inter-frame prediction and encoding,
- transcoding and processing - disruptions and transformations encountered during file transfers and processing across different platforms, often leading to additional noise or loss of fidelity.

A key component of advancing spatial domain video steganography is understanding the natural statistical variations between video frames (Yunxia, et al., 2018). Accurately characterizing this noise is crucial for determining the minimum level of inherent noise that can be expected, which in turn informs strategies for embedding information without compromising the integrity of the cover medium. By leveraging these statistical properties, researchers can develop methods that manipulate the medium's entropy, thereby improving the subtlety and resilience of the embedded message.

This study undertakes a comprehensive analysis of the natural statistical properties inherent in video covers, exploring their potential application in the design and refinement of spatial domain video steganography techniques. By examining how these properties can be exploited to minimize the impact of natural noise, the research seeks to enhance the robustness of information concealment strategies while maintaining high fidelity to the original content. The findings from this study aim to contribute to a deeper understanding of the mechanisms that govern effective video steganographic embedding, offering valuable insights for the optimization of these techniques in practical applications across diverse digital media platforms.

Assumptions

In the context of digital media representation, video content can be conceptualized as a sequential array of discrete images, commonly referred to as frames. However, this simplistic model diverges significantly from practical video storage methods employed by contemporary codecs. These advanced algorithms exploit inter-frame redundancies, often encoding only the differential information between successive frames rather than storing each frame in its entirety, thereby substantially reducing the requisite data volume for video storage and transmission. Notwithstanding these sophisticated compression techniques, for the purposes of this investigation, a simplified video model was adopted, eschewing advanced inter-frame compression mechanisms. This model, which aligns closely with the Motion JPEG (MJPEG) format, wherein each frame is independently compressed as a JPEG image, facilitates a more direct analysis of pixel color variations across consecutive frames. The selection of this straightforward approach offers several advantages in the context of steganographic research, including enhanced transparency in examining pixel-level modifications, analytical simplicity in tracking steganographic alterations throughout the video sequence, and improved generalizability of insights to a broader range of video formats and compression schemes. Consequently, this methodological choice provides a robust foundation for investigating spatial domain techniques in video steganography, while acknowledging the trade-off between model simplicity and real-world video compression complexity. In this study, we will use the definition of the histogram function $hist$ for the frequency of color differences between pixels in consecutive video frames, in accordance with the mathematical model proposed by Pery (2024).

For all studies, analyses, and experiments conducted within this research, video files were sourced from the publicly available database on pixabay.com, in compliance with its licensing terms permitting use for non-commercial purposes (Pixabay.com, 2024). A total of 666 video files were randomly selected from the platform, with the selection process guided by specific criteria to ensure diversity and representativeness. Videos were chosen from a broad range of thematic categories, encompassing various dynamic characteristics, motion patterns, and color profiles, to capture a wide spectrum of natural video properties. To maintain consistency, only videos encoded with the H.264 codec at a resolution of 1920x1080 were included. From each selected video file, the first 100 frames were extracted for detailed experimental analysis. This resulted in a comprehensive dataset comprising over 138 billion pixels across consecutive frames, providing a robust foundation for statistical evaluations and ensuring replicability of the study. The systematic selection and preparation of the video samples aim to enhance the reliability and generalizability of the findings while enabling other researchers to replicate the methodology using similarly structured datasets.

Experimental Results

Research Design

For all selected video files, the function $hist$ was calculated as defined by Pery (2024) and the resulting histograms were subsequently analyzed. The research design, consistently applied across various experiments in this study, involved processing all video covers such that, beginning with the second frame of each video file, differences between each consecutive frame and its preceding frame were calculated using the function $diff$ defined by Pery (2024). These differences were further analyzed at the levels of individual frames and the full database of video covers.

For each analysis, frequency distributions, histograms, and statistical indicators, including standard deviation, were calculated to characterize the properties of the variables studied. Specific analyses were chosen based on their potential applicability in the design and refinement of spatial domain video steganography methods.

Basic RGB Analyses

The first research experiment involved calculating the natural distribution of individual pixel colors. The results are presented as a histogram in Figure 1.

This experiment focused on independent frequency distributions for each color, without considering any interdependencies between changes in other pixel colors. The chart in Figure 1 also includes standard deviation values for the individual color difference frequencies, represented by lighter colors.

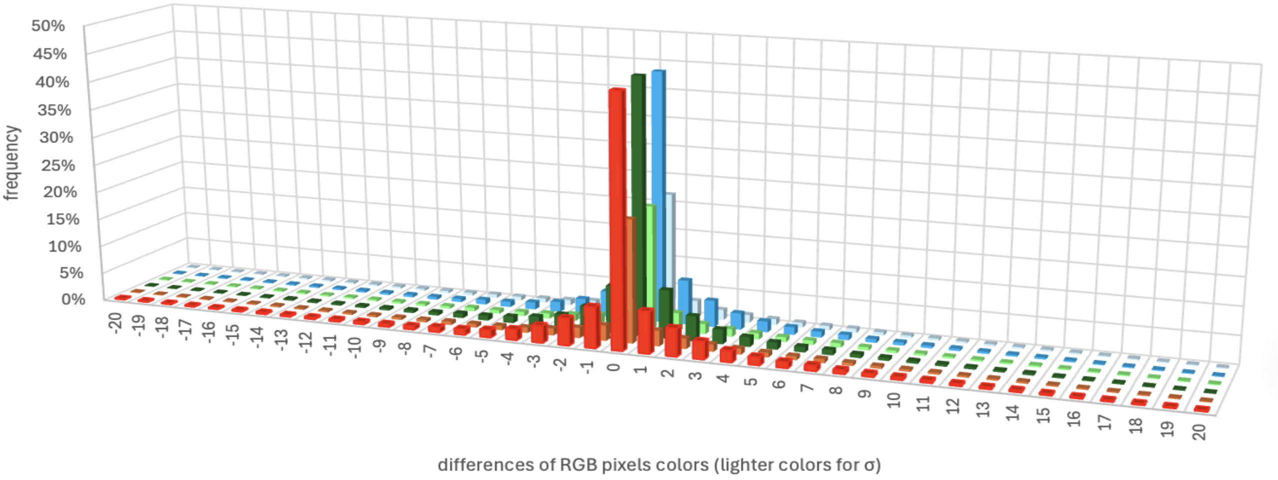

Fig. 1. Frequency of differences for RGB colors

For clarity of the charts, the histograms in Figure 1 were limited to differences within the range of [-20, 20]. This range accounts for over 93% of all the results obtained. The values are presented also in Table 1.

Table 1: Values of color pixel differences with corresponding standard deviations

difference	red color	green color	blue color	σ red color	σ green color	σ blue color
-20	0.16%	0.15%	0.16%	0.17%	0.17%	0.17%
-19	0.17%	0.17%	0.17%	0.18%	0.18%	0.18%
-18	0.18%	0.18%	0.18%	0.20%	0.19%	0.20%
-17	0.20%	0.20%	0.20%	0.21%	0.21%	0.21%
-16	0.22%	0.21%	0.22%	0.22%	0.22%	0.22%
-15	0.25%	0.24%	0.25%	0.25%	0.24%	0.25%
-14	0.30%	0.30%	0.31%	0.30%	0.30%	0.30%
-13	0.31%	0.30%	0.30%	0.29%	0.28%	0.29%
-12	0.34%	0.33%	0.34%	0.31%	0.31%	0.31%
-11	0.39%	0.38%	0.38%	0.34%	0.34%	0.34%
-10	0.44%	0.43%	0.44%	0.38%	0.37%	0.37%
-9	0.51%	0.49%	0.51%	0.42%	0.41%	0.41%
-8	0.61%	0.58%	0.60%	0.48%	0.47%	0.47%
-7	0.87%	0.82%	0.85%	0.63%	0.62%	0.63%
-6	0.99%	0.90%	0.96%	0.65%	0.64%	0.65%
-5	1.33%	1.17%	1.26%	0.78%	0.76%	0.78%
-4	1.92%	1.61%	1.81%	0.96%	0.94%	0.96%
-3	3.02%	2.46%	2.79%	1.25%	1.23%	1.24%
-2	4.82%	4.35%	4.59%	1.84%	1.75%	1.78%
-1	7.27%	8.45%	7.77%	2.75%	3.31%	3.01%
0	44.35%	45.28%	44.41%	21.76%	21.87%	21.89%
1	7.40%	8.60%	7.93%	2.78%	3.30%	3.01%
2	4.93%	4.48%	4.73%	1.84%	1.80%	1.83%
3	3.14%	2.59%	2.92%	1.31%	1.38%	1.36%
4	2.02%	1.73%	1.91%	1.05%	1.10%	1.07%
5	1.41%	1.27%	1.36%	0.84%	0.88%	0.87%
6	1.06%	0.99%	1.04%	0.69%	0.76%	0.77%
7	0.93%	0.91%	0.93%	0.69%	0.77%	0.73%
8	0.67%	0.65%	0.66%	0.53%	0.56%	0.55%
9	0.55%	0.53%	0.55%	0.44%	0.44%	0.45%
10	0.47%	0.45%	0.47%	0.39%	0.38%	0.39%
11	0.41%	0.39%	0.40%	0.35%	0.34%	0.35%
12	0.35%	0.34%	0.35%	0.32%	0.31%	0.32%
13	0.31%	0.31%	0.31%	0.29%	0.29%	0.29%
14	0.31%	0.31%	0.32%	0.31%	0.31%	0.31%
15	0.25%	0.25%	0.25%	0.26%	0.26%	0.26%
16	0.22%	0.22%	0.22%	0.23%	0.23%	0.23%
17	0.20%	0.20%	0.20%	0.21%	0.21%	0.21%
18	0.18%	0.18%	0.19%	0.20%	0.19%	0.20%
19	0.17%	0.17%	0.17%	0.18%	0.18%	0.18%
20	0.16%	0.15%	0.16%	0.17%	0.17%	0.17%

Analyses of RGB color difference combinations

The next experiment aimed to examine the frequency distributions of all possible combinations of pixel color differences. In the RGB space, coded with three bytes, the number of possible pixel difference combinations is $(255 + 1 + 255)^3$, amounting to over 133 million. For all video files, the frequency distributions of each possible combination were calculated and ordered by their distance from the (0,0,0) combination, where the distance was defined as the sum of the differences across all colors.

Table 2 presents the 30 combinations with the highest frequencies around the (0,0,0) combination, along with their corresponding standard deviation values.

Table 2: Frequency of combinations of colors differences with corresponding standard deviations

(R,G,B) difference	frequency	σ
(-1,-2,0)	0.19%	0.13%
(-3,0,0)	0.31%	0.23%
(0,0,-3)	0.09%	0.10%
(0,-1,-1)	0.10%	0.12%
(-2,0,0)	0.72%	0.47%
(0,0,-2)	0.24%	0.22%
(1,-2,-1)	0.10%	0.07%
(0,1,-3)	0.14%	0.12%
(-3,1,0)	0.11%	0.10%
(0,0,-1)	0.28%	0.27%
(-1,0,0)	0.22%	0.21%
(1,-1,-1)	0.21%	0.13%
(0,1,-2)	0.36%	0.29%
(-2,1,0)	0.24%	0.20%
(0,-2,1)	0.11%	0.10%
(0,0,0)	38.01%	22.56%
(0,-1,1)	0.63%	0.47%
(0,1,-1)	0.62%	0.47%
(-1,1,0)	0.22%	0.20%
(1,-1,0)	0.22%	0.20%
(0,0,1)	0.28%	0.27%
(1,0,0)	0.22%	0.20%
(-1,1,1)	0.22%	0.14%
(0,-1,2)	0.36%	0.29%
(2,-1,0)	0.24%	0.20%
(0,2,-1)	0.11%	0.10%
(0,1,1)	0.10%	0.12%
(1,1,0)	0.09%	0.12%
(2,0,0)	0.72%	0.46%
(0,0,2)	0.24%	0.22%
(-1,2,1)	0.11%	0.08%

Histograms of the 100 combinations with the highest frequency values, along with their corresponding standard deviation values, are presented in Figure 2.

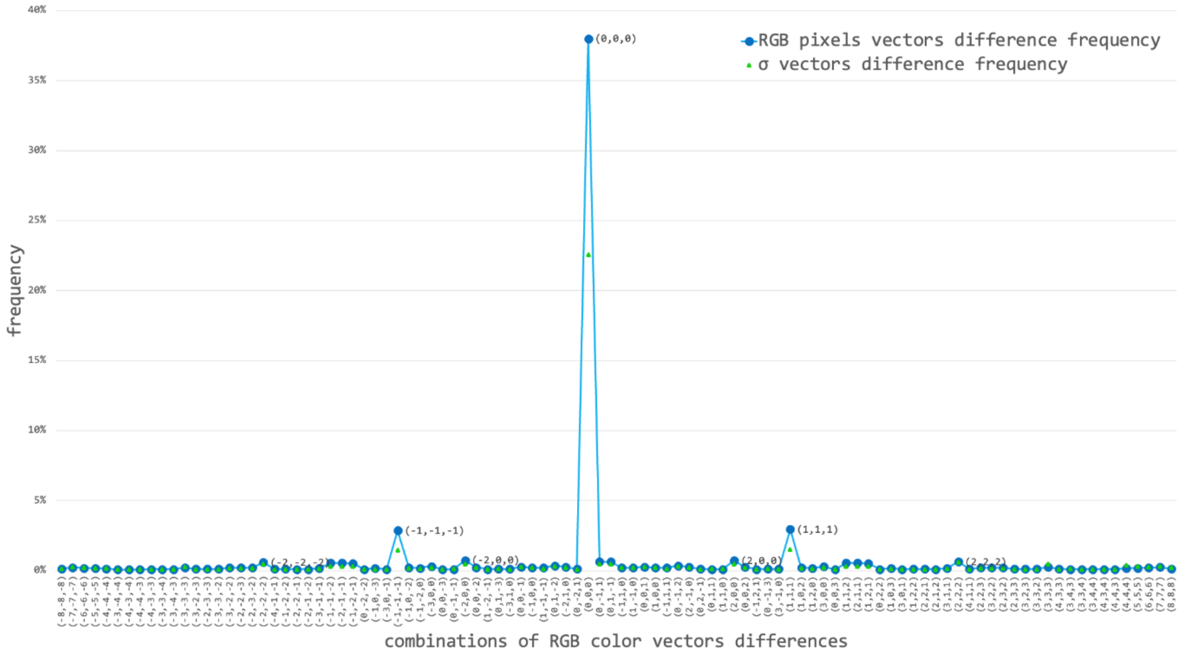

Fig. 2. Frequency of combinations of RGB color differences

Figure 3 presents the same values as Figure 2, but with the (0,0,0) combination excluded, allowing for a clearer view of the differences between various pixel color difference combinations on a larger scale.

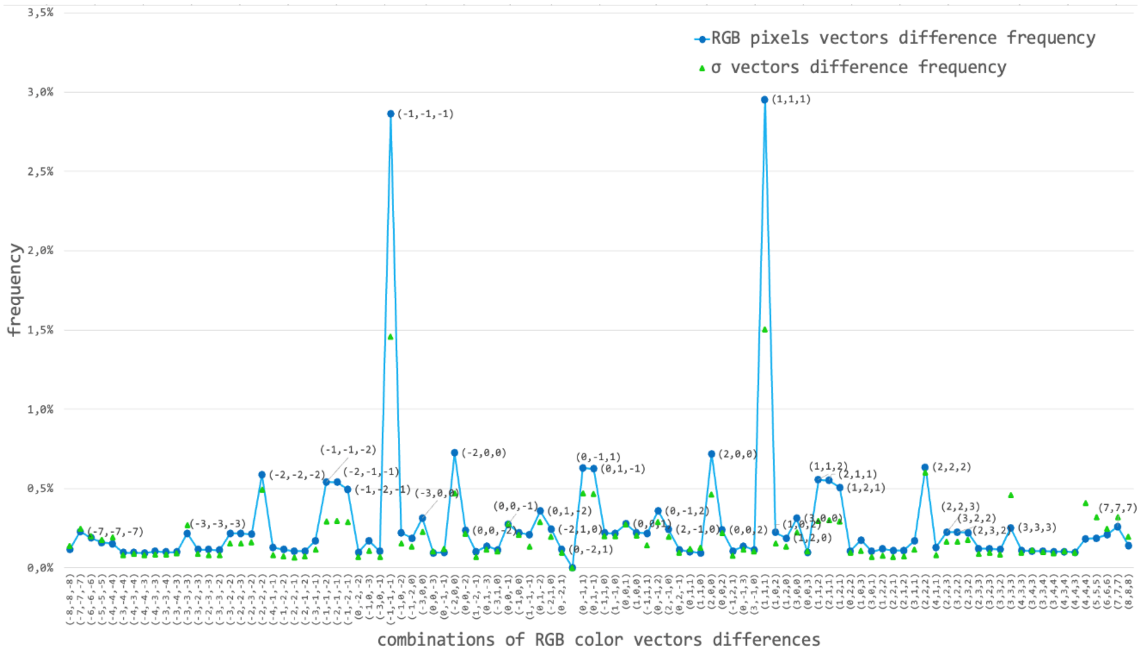

Fig. 3. Frequency of combinations of RGB color differences without (0,0,0) combination

Analyses of selected groups of RGB color difference combinations

From the perspective of video steganography techniques, certain characteristic groups of color difference combinations are of particular interest, as they potentially enable efficient encoding and subsequent decoding of information bits. This is especially important considering that information between consecutive frames in a video file may be subject to disturbances or transformations. The following groups of color differences were analyzed:

– a difference of 0 (no change in pixel color between frames), denoted by the symbol "·",

- a difference less than 0 (increase in color value in the next frame), denoted by the symbol "-",
- a difference greater than 0 (decrease in color value in the next frame), denoted by the symbol "+".

There are a total of 27 defined groups of combinations: ---, --·, --+, -·-, -··, -·+, -+-, -+·, -++, ·--, ·-·, ·-+, ··-, ···, ··+, ·+-, ·+·, ·++, +--, +-·, +-+, +·-, +··, +·+, ++-, ++·, +++. Frequency distributions and standard deviations were calculated for each of these groups. The results are presented in Table 3 and illustrated in Figure 4.

Table 3: Frequency of groups of color differences with corresponding standard deviations

groups	frequency	σ
---	19.48%	10.11%
--·	0.87%	0.61%
--+	1.06%	0.90%
-·-	1.25%	0.73%
-··	1.32%	0.84%
-·+	0.40%	0.34%
-+-	0.89%	0.91%
-+·	0.89%	0.58%
-++	1.23%	0.93%
·--	0.87%	0.97%
·-·	0.12%	0.15%
·-+	1.50%	1.02%
··-	0.66%	0.60%
···	38.01%	22.56%
··+	0.66%	0.61%
·+-	1.49%	1.02%
·+·	0.12%	0.15%
·++	0.92%	1.02%
+--	1.20%	0.93%
+-·	0.88%	0.59%
+-+	0.88%	0.91%
+·-	0.40%	0.33%
+··	1.32%	0.83%
+·+	1.26%	0.72%
++-	1.06%	0.89%
++·	0.88%	0.69%
+++	20.37%	10.26%

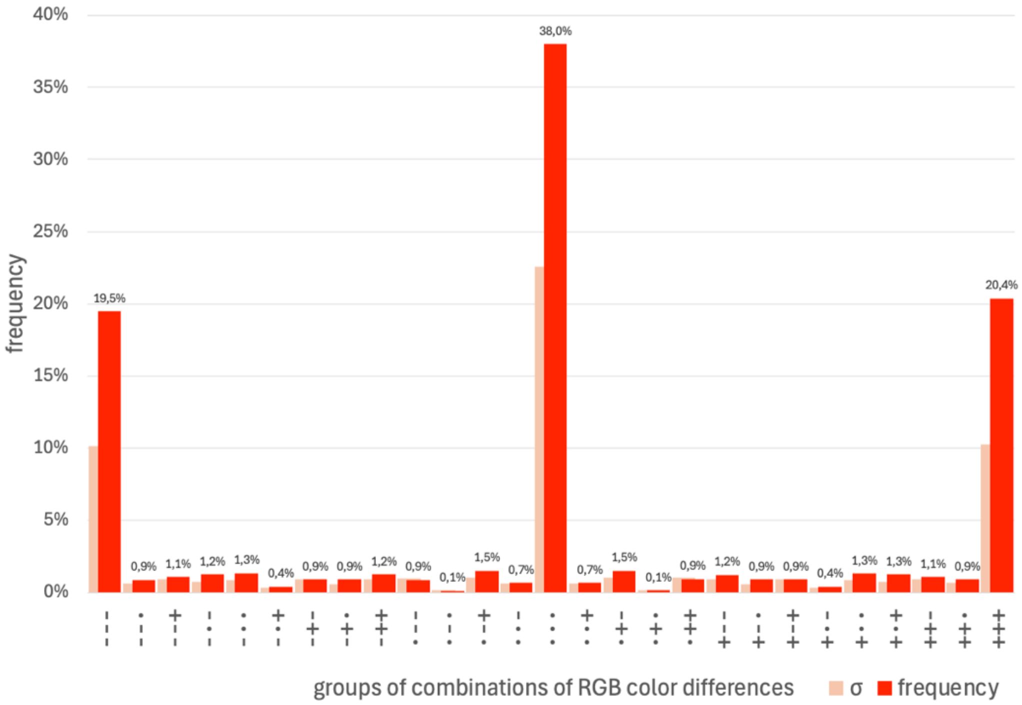

Fig. 4. Frequency of groups of combinations of RGB color differences

Discussion

The distributions of frequency differences for individual RGB colors between consecutive video frames, as presented in Table 1 and Figure 1, indicate that:

- The frequency distributions for individual colors are very similar to each other, suggesting a natural regularity from which deviations may serve as a method for encoding information.
- The frequency of differences decreases asymptotically and almost symmetrically on both sides, approaching values close to zero. This aligns with the intuitive understanding that most color changes between consecutive frames are minimal.

In contrast, the results shown in Table 2, in Figure 2 and in Figure 3 illustrate the frequency distributions for different combinations of differences across the three RGB colors. It is evident that, unlike the distributions of variations in individual color differences, where regularity and monotonicity were observed, there are distinctive color combinations with significantly higher or lower frequencies of occurrence. Identifying such irregularities was one of the objectives of this study, as they could potentially be utilized for information encoding by steganographic algorithms. For example, the combination (2,1,1), which naturally occurs at an average frequency of 0.5%, could, after applying a coding algorithm, reach a value of 0.1%. Such a change might remain undetected, allowing for the embedding of a portion of information.

The final set of experiments shown in Table 3 and in Figure 4 involved calculating the frequencies of defined patterns, representing all possible situations where each color in the following video frame has three degrees of freedom: remains the same, decreases, or increases. This results in a total of 27 groups, among which, for potential use in video steganography, the ones that represent changes across all colors can be distinguished: "+++", "++-", "+-+", "-++", "+--", "-+-", "--+", "---". From the frequency distributions, the most suitable for steganographic encoding would be the groups "++-", "+-+", "-++", "+--", "-+-", "--+" due to their moderate frequencies and possibilities to code bits information - the change of value from "+" to "-" and vice versa enables efficient encoding of hidden information bits as 1s and 0s.

For all calculated distributions, whether for individual colors, combinations, or groups, the standard deviations of the distribution values are relatively high, oscillating around half of the mean values. This is a natural feature associated with the fundamental property of video, which is the encoding of variations between consecutive frames that create the effect of motion and smooth playback. Differences between films in terms of color, dynamics, and other factors result in varying characteristics of changes between frames. This effect implies that in steganographic techniques utilizing color changes of pixels across consecutive frames, it is essential to handle a significant amount of natural noise. One of the best potential solutions to this problem is an adaptive approach, where the encoding method is adjusted to the local properties of the specific video file, including the statistical characteristics of pixel color variability across its consecutive frames.

Conclusions

In this study, we examined video files to analyze the variability of pixel color values across consecutive video frames. By investigating a large, randomly selected sample of video files chosen to ensure diversity in various aspects and parameters - such as dynamic content and color characteristics - we were able to establish that there are distinctive frequency values for certain combinations of color changes or defined groups of these combinations. The presence of natural differences between such combinations of color variations in video files provides deeper insights into the nature of potential disturbances that may affect the transmission of encoded information between successive video frames. Additionally, this understanding can facilitate the improvement and development of new methods for information encoding, such as those based on statistical changes in frequency distributions.

Theoretical Contributions

This study conducted an analysis of the frequency distributions of naturally occurring color differences between pixels in consecutive video frames. We determined histograms and identified characteristic frequencies for individual colors, specific combinations, and selected groups of combinations. Given that the research was performed on a large sample of random video files, it can be inferred that the calculated frequency characteristics describe natural features of video files encoded with the H.264 codec.

Practical Implications

The calculated and presented results on the characteristics of frame variability in video files may be utilized to enhance current techniques and develop new methods of video steganography that operate in the spatial domain, leveraging changes in pixel color values encoded within the RGB space to conceal information. By understanding the natural frequency distributions of color variations, it is possible to design more sophisticated methods for embedding hidden messages.

Future Research

We propose the following directions for future investigation:

- **Sensitivity analysis**. Investigating whether the calculated characteristics are influenced by specific attributes of video files, such as dynamic content and color schemes, as well as technical parameters like resolution, frame rate, and encoding settings. A deeper understanding of these factors could lead to the development of more robust video steganographic methods applicable to diverse video formats, with particular attention to the impact of codecs not analyzed in this study, such as H.265.
- **Development of video steganography techniques**. Designing innovative steganographic methods that leverage changes in selected groups of color difference combinations to encode information within video steganograms. By focusing on patterns that integrate seamlessly into the natural variability of video content, these techniques could enhance both the efficiency and imperceptibility of hidden data transmission.
- **Resilience against attacks**. Exploring the robustness of these methods against potential attacks and advanced steganalysis techniques to ensure their practical applicability in secure data communication.
- **Empirical validation**. Conducting further empirical studies to evaluate the effectiveness of these methods in real-world scenarios, particularly in the context of specific steganographic approaches. Such evidence would provide a strong foundation for refining the proposed techniques and confirming their utility in practical applications.

Author Contributions

The results of the work were obtained mainly by the first author under the scientific supervision of the second one.

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