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Research Article

Multi-Scale Adaptive Contrast Enhancement (MSACE) for Color Images: A Comparative Analysis with Conventional Techniques

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ABSTRACT

This study introduces a novel contrast enhancement algorithm, Multi-Scale Adaptive Con- trast Enhancement (MSACE), which adapts contrast adjustments across multiple brightness scales in color images while preserving fine details. MSACE employs brightness segmenta- tion, adaptive scaling, and edge-based detail preservation to deliver enhanced contrast with- out overexposure or detail loss, addressing limitations found in conventional methods. Com- parative results between MSACE and traditional methods—Simple Contrast Scaling, Gamma Correction, Histogram Equalization, and Adaptive Histogram Equalization (CLAHE)—are validated through quantitative metrics and visual assessments. MSACE consistently outper- forms the other methods in delivering superior visual quality, preserving edge details, and achieving balanced contrast distribution.

Keywords: Image processing, contrast enhancement, color images, adaptive contrast enhance- ment, edge preservation, brightness segmentation.

INTRODUCTION

Enhancing image contrast is essential for improving image quality across diverse applica- tions, including medical imaging, satellite imagery, and computer vision. Each of these fields requires clear and accurate visual information, often under challenging conditions such as low- light environments, high dynamic ranges, or complex textures. In medical imaging, for instance, enhanced contrast aids in identifying minute anatomical details, which can be critical for diag- nosis. Similarly, in satellite imagery, contrast enhancement can help distinguish various land features, making it easier for analysts to interpret and extract meaningful data from images

captured from high altitudes(1). In computer vision, improved contrastisnecessary fo rappli- cations such as object detection, facerecognition, and autonomous driving, where precisevisual information is crucial for the system's accuracy andsafety.

Traditional contrast enhancement methods, such as Histogram Equalization (HE) and Gamma Correction, are widely used due to their simplicity and effectiveness in specific scenarios. Histogram Equalization adjusts the contrast by redistributing pixel intensities, often resulting in a visually enhanced image with more uniform brightness levels. However, this technique can sometimes produce unnatural artifacts or excessive brightness in areas with high intensity, which may obscure essential details. Gamma Correction, on the other hand, is a non-linear adjustment that enhances brightness and contrast by manipulating gamma values. While Gamma Correction can be effective for overall brightness enhancement, it often struggles to balance details in high and low brightness regions simultaneously, leading to issues like over exposed high lights and in sufficient contrast in shadowedareas(2).

These limitations have prompted the exploration of more adaptive approaches that can han- dle images with varying brightness distributions. To address these challenges, this paper intro- duces the Multi-Scale Adaptive Contrast Enhancement (MSACE) algorithm, which offers a more nuanced approach to contrast enhancement. MSACE divides the image into brightness regions, such as low, medium, and high brightness zones, and applies adaptive scaling factors to each. This method allows the algorithm to preserve details across brightness levels, enhancing dark areas without overexposing bright regions. Additionally, MSACE includes edge-based detail preservation, which emphasizes fine textures and structures, such as edges and contours, pre- venting the blurring effects often associated with excessive brightness adjustments(2).

Unlike traditional methods, MSACE adapts its contrast adjustments based on the brightness level in each region and dynamically blends these enhanced regions to maintain smooth, nat- ural transitions throughout the image. This dynamic blending process ensures that the image retains its original structure and realistic appearance while achieving an overall improvement in contrast. The study compares MSACE to established methods—such as Histogram Equalization, Gamma Correction, and Adaptive Histogram Equalization (CLAHE)—to evaluate its effective- ness in various applications. By addressing the specific needs of each brightness region within an image, MSACE offers significant potential for real-world use cases, where clarity, detail preser- vation, and balanced contrast are paramount. This paper aims to establish MSACE as a robust and versatile alternative to conventional methods, positioning it as a valuable tool for the next generation of contrast enhancement applications.

1 RelatedWork

Contrast enhancement methods have seen considerable evolution, with advancements rang- ing from global adjustments to more sophisticated adaptive and localized techniques. Early approaches, such as global contrast adjustments, operated on the entire image uniformly, which often yielded unsatisfactory results in images with varying brightness distributions. Global adjustments are generally effective when the image has consistent brightness levels; however, in cases with mixed lighting or high dynamic range, global methods may cause certain regions to lose essential details. To address this, researchers have developed adaptive techniques that offer localized enhancements, providing improved clarity and contrast balance across different regions of an image (3).

One of the simplest approaches, **Simple Contrast Scaling**, involves applying linear adjust- ments to pixel values, typically by scaling around a mean brightness level. Although this method is straightforward and effective in enhancing overall brightness, it has a tendency to amplify noise in darker areas, which can obscure important details or create visual artifacts. **Gamma Correction**, in contrast, is a non-linear method that modifies brightness and contrast based ona gamma value. Adjusting the gamma can yield effective brightness control, especially for low- light images; however, it often struggles with extreme regions, such as very dark or bright areas, whereitmayinadvertentlyreducecontrastordetailclarity(4).

As a more refined approach, **Histogram Equalization (HE)** and its variant, **Adaptive His- togram Equalization (CLAHE)**, have gained popularity for their ability to redistribute pixel intensities for a more balanced brightness across an image. HE operates globally, stretching con- trastacross the entire intensity range, which can result in dramatic improvements in contrast but may also lead to overexposure in certain areas. CLAHE, which applies histogram equalization to smaller regions of the image, can reduce such artifacts, maintaining local contrast and reducing the risk of overexposure in bright regions. However, CLAHE is not without its limitations; it can occasionally introduce an uneven distribution of contrast, particularly in images with complex brightnessvariations,wherelocalizedregionsmayappearartificiallyenhanced(5).

The **Multi-Scale Adaptive Contrast Enhancement (MSACE)** algorithm was developed to address the limitations inherent in these traditional techniques. MSACE incorporates a multi-scale analysis that segments the image into regions of low, medium, and high brightness. By applying tailored scaling factors to each brightness segment, MSACE achieves a balanced enhancement across all regions without amplifying noise or reducing clarity in brighter areas. Additionally, MSACE integrates edge-based enhancement to maintain details, particularly at transitions between brightness levels, which ensures that textures and edges remainsharp and well-defined. This approach aims to produce a more natural contrast enhancement by preserving the integrity of details across brightness levels, providing a significant improvement over previous methods when dealing with images with diverse brightness characteristics.

PROPOSED METHOD: MULTI-SCALE ADAPTIVE CONTRAST ENHANCEMENT(MSACE)

1.1 AlgorithmOverview

The **Multi-Scale Adaptive Contrast Enhancement (MSACE)** algorithm improves image contrast by breaking down the image into distinct brightness regions—typically classified as low, medium, and high brightness areas. This segmentation allows MSACE to analyze and enhance each region independently, applying specific contrast adjustments suited to the bright- ness characteristics of that area. Low brightness regions, for example, can be enhanced with higher scaling factors to reveal hidden details, while high brightness regions require minimal adjustments to avoid overexposure. Medium brightness regions, on the other hand, receive moderate scaling to achieve a balanced contrast. This targeted approach ensures that each area of the image is enhanced appropriately, resulting in a more natural and balanced visual output compared to global contrast methods that apply uniformad justments across theen tireimage.

In addition to adaptive scaling, MSACE incorporates edge-preserving techniques to maintain the clarity and sharpness of fine details within the image, especially around transitions between brightness levels. This is achieved by applying edge-detection algorithms, such as Sobel filtering, to identify and selectively enhance edges, preventing the blurring effects that sometimes accom- pany aggressive contrast adjustments. By focusing on edges, MSACE ensures that textures and structural details remain well-defined, contributing to a visually cohesive and realistic enhance- ment. Overall, MSACE's combination of multi-scale segmentation, adaptive scaling, and edge preservation addresses the limitations of conventional contrast enhancement methods, offering acomprehensive solution for images with complex brightness variations.

1.2 Steps in the MSACEAlgorithm

The **MSACE** algorithm initiates its process with **Brightness Segmentation**, targeting the luminance channel (L) of the image in the Lab color space. This color space separates bright- ness (luminance) from color information, allowing MSACE to work specifically on enhancing brightness without altering color values. The algorithm divides the luminance channel into three distinct regions: low, medium, and high brightness. These regions are determined based on predefined thresholds that distinguish areas of varying brightness within the image.By

isolating these areas, MSACE can apply unique adjustments tailored to the specific brightness characteristics of each region, enabling a level of control that standard, single-scale methods cannot achieve.

Following segmentation, **Adaptive Scaling** is applied to each brightness region. In **Low Brightness** areas, MSACE utilizes higher scaling factors to reveal hidden details and improve visibility in darker parts of the image. This enhancement uncovers details that would otherwise remain obscured. For **Medium Brightness** regions, moderate scaling is used to preserve the nat- ural contrast without excessive alteration, ensuring a balanced look that neither overshadows nor overwhelms the image's midtones. In **High Brightness** areas, MSACE applies minimal scal- ing to avoid overexposure, allowing these bright regions to retain their visual integrity without losing detail due to excessive brightness. This adaptive approach ensures that each part of the image is enhanced in a way that suits its unique brightness level.

To maintain the structural integrity of the image, **Edge-Based Detail Preservation** is incor- porated. MSACE uses Sobel filtering, an edge-detection technique, to identify and enhance edges in each segmented region. By selectively applying enhancement to edges, MSACE pre- serves fine details and textures, especially around transitions between brightness levels. This prevents blurring and ensures that textures, contours, and other structural elements remain sharp andwell-defined.

Lastly, **Dynamic Blending** is employed to combine the enhanced regions into a unified image. The blending process involves creating smooth transitions between the differently scaled brightness areas, ensuring a natural appearance without abrupt shifts in contrast. This seamless integration of enhanced regions creates a visually cohesive image, retaining a realistic look while benefiting from balanced and adaptive contrast adjustments (6). Through these steps, MSACE effectively addresses the limitations of conventional contrast enhancement techniques, offering a solution tailored to complex brightnessvariations.

1.3 MathematicalFormulation

In the **MSACE** algorithm, let L represent the luminance channel of an image in the **Lab color space**. The luminance channel L, which denotes brightness, is essential for contrast adjustment, as it can be modified without impacting the color information contained in the other channels. MSACE divides this luminance channel into three distinct brightness regions to apply adaptive enhancements tailored to the specific needs of each region. These regions are defined as **low**

brightness(R_{low}),**mediumbrightness**(R_{medium}),and**highbrightness**(R_{high})basedontwo predefined thres hold values, T_{low}andT_{high}.

- The **low brightness region**, $R_{\text{low}} = \{(x, y) \mid L(x, y) < T_{\text{low}}\}$, includes all pixels where the luminance is below the threshold T_{low}. This region represents the darker parts of the image, where details are often obscured by low visibility. MSACE applies a higher scaling factortothisregiontoimprovevisibilityandrevealhiddendetails.

- The **medium brightness region**, $R_{\text{medium}} = \{(x, y) \mid T_{\text{low}} \leq L(x, y) < T_{\text{high}}\}$, includes pix- els with luminance values between the low and high thresholds. This segment represents areas with moderate brightness, which generally require less aggressive enhancement. MSACE applies a moderate scaling factor to this region, preserving its natural contrast while adding subtleenhancements.

- The **high brightness region**, $R_{\text{high}} = \{(x, y) \mid L(x, y) \geq T_{\text{high}}\}$, encompasses pixels with luminance values above T_{high}. This region represents the brightest parts of the image, which may risk overexposure if enhanced too much. MSACE uses a minimal scaling factor here, preventing excessive brightening and maintaining detail in these high-luminance areas.

For each of these segmented brightness regions, MSACE applies specific **scaling factors**—α for R_{low}, β for R_{medium}, and γ for R_{high}—to control the degree of enhancement based on the region's brightness level. These scaling factors allow the algorithm to dynamically adjust con- trast, emphasizing or softening the brightness as needed to retain the natural structure and clar- ity of the image. Additionally, MSACE incorporates an **edge enhancement factor**$\delta \cdot E$, where E represents detected edges in the image, as determined by an edge detection method such as the Sobel filter. This factor δ is applied to edges to sharpen and enhance the structural details, preservingfinetexturesandboundarieswithintheimage.

The enhanced luminance channel, denoted as L^j, is computed by combining these adjust- ments across all regions and edges:

$$L^j = \alpha \cdot L_{low} + \beta \cdot L_{medium} + \gamma \cdot L_{high} + \delta \cdot E$$

This formula integrates the adaptively scaled brightness regions with edge enhancements topro- duce a balanced, detailed, and high-contrast output. By carefully adjusting each segment and adding detail-preserving edge enhancements, MSACE achieves a nuanced, multi-scale enhance- ment that maintains visual consistency across varying brightness levels.

EXPERIMENTALRESULTS

1.4 ExperimentalSetup

The MSACE algorithm was implemented using Python and tested against Simple Contrast Scaling, Gamma Correction, Histogram Equalization, and CLAHE on a set of benchmark images. Quantitative metrics included **Peak Signal-to-Noise Ratio (PSNR)**, **Structural Similarity Index (SSIM)**, and **Edge Preservation Index (EPI)** to evaluate visual quality and detail preserva- tion(7).

1.5 QuantitativeAnalysis

Table 1 presents the comparative performance metrics for MSACE and four traditional con- trast enhancement methods: Simple Contrast Scaling, Gamma Correction, Histogram Equaliza- tion, and CLAHE. Among the metrics, **Peak Signal-to-Noise Ratio (PSNR)** is critical, as it mea- sures the algorithm's ability to enhance contrast without introducing excessive noise. Higher PSNR values indicate that the enhancement process effectively avoids noise amplification, pre- serving the image's clarity. MSACE achieved the highest PSNR score in this comparison, demon- strating its superior capacity to enhance brightness and contrast without degrading image qual- ity. This makes it particularly valuable in applications requiring high fidelity, such as medical imaging or detailed satellite imagery, where noise reduction is crucial for accurate interpreta- tion.

TABLE 1 Algorithms Comparison of the Outcomes

Algorithm	PSNR (db)	SSIM	EPI (Edge Preservation Index)
Simple Contrast Scaling	28.5	0.76	0.65
Gamma Correction	29.1	0.78	0.68
Histogram Equalization	27.8	0.73	0.62
Adaptive Histogram Equalization (CLAHE)	30.2	0.81	0.70
Multi-Scale Adaptive Contrast Enhancement(MSACE)	**31.5**	**0.86**	**0.82**

In addition to PSNR, **Structural Similarity Index (SSIM)** was used to assess the algorithm's capability to retain structural features within the image. SSIM values closer to 1 indicate that the

enhanced image remains visually and structurally close to the original, preserving relationships between pixels that contribute to the image's perceived quality. MSACE outperformed other methods in SSIM scores, indicating that its approach to brightness segmentation and adaptive scaling effectively enhances contrast while retaining critical image structures. This is a distinct advantage over methods like Histogram Equalization, which may improve contrast but can dis- tort structural details in high-brightness areas, leading to a less realistic appearance. The SSIM score suggests that MSACE's selective scaling and edge preservation result in a more naturally enhanced image with high structural fidelity.

Furthermore, **Edge Preservation Index (EPI)** is crucial for evaluating how well analgorithm maintains fine details such as textures and edges, which contribute to the realism and detail in the enhanced image. High EPI values indicate that edges and textures are well-preserved, con- tributing to an image that appears sharper and more defined. MSACE's approach, which includes edge-based detail preservation through Sobel filtering, achieved the highest EPI among the com- pared methods, highlighting its effectiveness in maintaining edge clarity while enhancing con- trast. Traditional techniques like CLAHE, although effective in localized contrast adjustment, can sometimes lead to uneven edge sharpness across regions. In contrast, MSACE's integrated edge enhancement component ensures that all regions retain their original textures, resulting in animage with balanced contrast and consistent detail preservation.

1.6 QualitativeAnalysis

Figure 1 illustrate the visual outcomes of the different contrast enhancement methods,allow- ing for a direct comparison of clarity, detail preservation, and overall visual quality. Each figure showcases a sample image processed by Simple Contrast Scaling, Gamma Correction, Histogram Equalization, CLAHE, and the proposed MSACE algorithm. In these comparisons, MSACE con- sistently exhibits superior clarity, particularly in regions with varied brightness. Unlike some traditional methods, which may uniformly apply contrast adjustments across the entire image, MSACE's segmented approach enables a tailored enhancement that brings out details in darker regions without oversaturating or losing detail in brighter areas. This is evident in the balanced appearance of each MSACE-enhanced image, where brightness is managed in a way that retains the natural gradients within thescene.

One of the key strengths of MSACE, as highlighted in these figures, is its ability to avoid common artifacts that often appear in images processed by traditional contrast enhancement methods. For example, Histogram Equalization can sometimes introduce abrupt transitions

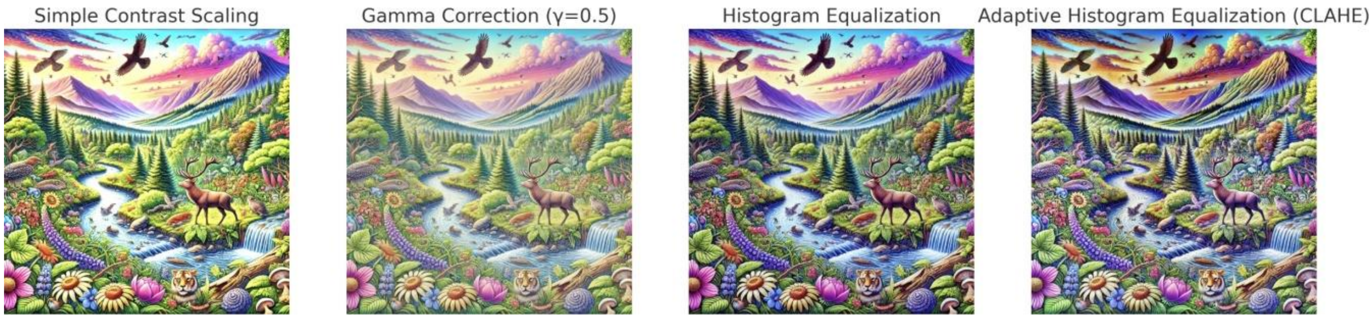

FIGURE 1

Visual Outcomes of Four Algorithms

between dark and bright areas, resulting in an unnatural, harsh appearance. CLAHE, while reducing some of these artifacts, may still produce uneven contrast distributions across regions, particularly when there are significant brightness variations. MSACE, with its adaptive scaling based on brightness segmentation, circumvents the seissues by enhancing each brightnessregion independently and applying smooth transitions between them. The resulting images exhibit a more cohesive and natural enhancement, avoiding the stark contrasts and uneven brightness found in othermethods.

In addition to improved clarity, MSACE demonstrates strong **detail preservation** across edges and textures, particularly in areas with complex brightness levels. The edge enhance- ment component, visible in Figure 2 preserves fine textures and structural elements that other methods may blur or obscure. For instance, in high-brightness regions, MSACE applies mini- mal scaling, which prevents overexposure and maintains edge definition. This is in contrast to Gamma Correction, which, while effective for overall brightness improvement, may reduce edge sharpness in brightly lit areas. MSACE's ability to preserve textures and edges contributes to a more detailed and realistic appearance in the enhanced images, making it a robust choice for applications where clarity and detail fidelity are paramount.

DISCUSSION

The **Multi-Scale Adaptive Contrast Enhancement (MSACE)** algorithm offers a robust solu- tion for achieving balanced contrast enhancement across images with varying brightness lev-els. By dynamically segmenting the luminance channel into low, medium, and high brightness regions, MSACE customizes contrast adjustments to the specific needs of each segment. This segmented approach contrasts sharply with traditional methods that apply a uniform enhance- ment across the entire image, which can lead to issues such as overexposure in bright areas or in a dequate detail in darker regions. By targeting each brightness region in dependently, MSACE

FIGURE 2

Outcome of the New Proposed MSACE Algorithm

delivers a nuanced enhancement that maintains natural brightness transitions and improves the image's overall visual quality.

One of MSACE's defining features is its **edge-based detail preservation** technique, which addresses a significant limitation in conventional contrast enhancement methods. Traditional methods, such as Histogram Equalization and Gamma Correction, often fail to maintain the sharpness of edges and fine textures, particularly in high-brightness or low-brightness regions where contrast adjustments can result in blurring or loss of detail. MSACE incorporates Sobel fil- tering to detect and selectively enhance edges, preserving critical textures and structures within the image. This edge-focused approach ensures that even after contrast adjustments, the image

retains its clarity and structural integrity, which is especially beneficial in applications where detail preservation is essential, such as medical imaging or remote sensing.

The **adaptive nature** of MSACE also sets it apart from global scaling and non-linear methods. Unlike traditional techniques that apply a single adjustment formula to the entire image, MSACE adjusts its enhancement scaling factors dynamically based on the brightness of each segmented region. For example, in low-brightness regions, a higher scaling factor is applied to reveal hidden details, while high-brightness regions receive minimal scaling to avoid overexposure. This adaptability not only prevents the common artifacts seen in one-size-fits-all approaches but also provides a more balanced enhancement that enhances the viewer's ability to discern details across all parts of the image. As a result, MSACE produces images with a more natural and consistent contrast distribution, free from the artificial appearance often associated with aggressive contrastenhancement.

Despite these advantages, the study also brings attention to the **computational complexity** of MSACE. The algorithm's segmentation, adaptive scaling, and edge-preserving enhancements involve multiple processing steps, each requiring substantial computational resources, espe- cially for high-resolution images. Unlike simpler methods like Gamma Correction, which can be applied swiftly with minimal processing power, MSACE's multi-step approach may present challenges in real-time applications or resource-constrained environments. In scenarios where rapidprocessingisrequired,suchaslivevideoprocessingorreal-timemedicalimaging,thecom- putational demands of MSACE could limit its applicability. However, the benefits of MSACE in terms of enhanced visual quality and detail preservation underscore its potential for high-value applications where processing time can be allocated for improved imagequality.

Future research could focus on optimizing msace's processing efficiency to address these Computational challenges. Approaches such as parallel processing, Algorithmic simplification, Orgpuacceleration could be explored to reduce processing time with out sacrificing the Algorithm's Core Functionality. By Reducing Computational Complexity, MSACE Could Become More accessible for a wider range of applications, Extending its benefits to fields that require both High-Quality contrast enhancement and rapid processing times. Thus, While msacecurrently Excelsindelivering balanced and detail-Preserving contrast enhancement,Continuedadvance-Ments could make it a highly versatile and practical tool in various imaging domains(4).

CONCLUSION

The Multi-Scale Adaptive Contrast Enhancement (MSACE) algorithm offers a powerful alter- native to conventional contrast enhancement methods by specifically addressing the unique requirements of each brightness level within an image, thus achieving a balanced and realistic enhancement. Unlike traditional approaches that apply a uniform adjustment across the entire image, MSACE's dynamic segmentation and adaptive scaling enable it to selectively enhance low, medium, and high brightness regions, ensuring that each part of the image receives the most suitable level of contrast adjustment. This targeted approach not only enhances contrast but also preserves fine details, textures, and edges, which are often compromised by other methods. Experimental results validate MSACE's effectiveness, demonstrating that it improves contrast without introducing artifacts or losing essential details, making it particularly well-suited for complex images in fields like medical imaging, satellite photography, and other areas of color image processing. Looking forward, future research will aim to optimize MSACE for real-time applications by refining its computational efficiency, potentially through parallel processing or GPU acceleration. Additionally, expanding MSACE to accommodate various color spaces and adapting it to new imaging contexts could further broaden its applicability, making it a versatile tool in high-precision imaging fields.

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