ENHANCING MARS SURFACE IMAGERY: EVALUATING THE EFFICACY OF HISTOGRAM EQUALIZATION TECHNIQUES THROUGH PSNR ANALYSIS AND STATISTICAL TESTS

Abstract

This research investigates the effectiveness of histogram equalization methods for improving the clarity and detail of color images portraying the Martian landscape. Utilizing contrast stretching, histogram equalization, and adaptive equalization processes, we evaluated their impact on image enhancement. We quantified the effectiveness of these techniques by computing the original colour fractions and those post-enhancement for the red, green, and blue channels. Furthermore, we employed peak signal-to-noise ratio (PSNR) calculations to gauge the quality improvement achieved by histogram equalization compared to the original images. Subsequently, PSNR values were computed for each enhanced image column, derived from the R, G and B channels, encompassing PSNR_Contrast Stretching, PSNR_Histogram Equalization, and PSNR_Adaptive Equalization techniques. Statistical analyses, including paired t-tests, one-way ANOVA, Kruskal-Wallis tests, and independent t-tests, were conducted to compare original and enhanced colour fractions and PSNR values. Our findings revealed significant improvements in image quality post-histogram equalization, supported by notable enhancements in colour fractions and PSNR values. Moreover, statistical tests unveiled significant differences between original and enhanced colour fractions, as well as variations in the effectiveness of different histogram equalization methods. This research emphasizes the significance of quantitative evaluation in image processing contexts and highlights the capability of histogram equalization techniques to improve imagery of the Martian surface.

Keywords: Histogram equalization, PSNR, Statistical tests, Martian surface, image processing.

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I. INTRODUCTION

Mars, the neighboring planet, has long fascinated scientists, with ongoing exploration endeavors yielding a plethora of captivating images that reveal the mysteries of its surface. The images obtained by orbiters, rovers, and landers orbiting, exploring, and landing on Mars provide crucial information about the planet's geological formations, atmospheric conditions, and the possibility of supporting life. Mars surface imagery encompasses a wide range of landscapes, including ancient riverbeds, towering mountains, expansive plains, and captivating geological formations. Each image acts as a portal into Mars' history and current state, providing insights into ancient water activity, volcanic phenomena, and the possibility of microbial life. Nevertheless, the surface of Mars is not without its difficulties. Elements like image noise, uneven lighting conditions, and atmospheric interference can obscure details and impede scientific interpretation. To tackle these obstacles and optimize the use of Martian imagery, sophisticated image processing techniques, such as histogram equalization methods, are utilized to enhance image quality, enhance contrast, and uncover concealed details.

This research paper examines the effectiveness of histogram equalization techniques in enhancing the quality of images captured from the surface of Mars. Histogram equalization improves image contrast and visual appeal by redistributing pixel values across the entire range of colors. By extending the histogram to encompass all possible values, the contrast of the image is enhanced, leading to improved visibility of intricate details [1]. An image histogram is a graphical representation that displays the frequency of pixel intensities within an image, typically using an x-axis ranging from 0 to 255 for grayscale images and separate histograms for each color channel in color images. The y-axis represents the number of pixels with a particular intensity, with higher peaks indicating a greater number of pixels with that intensity. This visual representation provides valuable information about the image's contrast and brightness, with the histogram's shape revealing details such as brightness levels and contrast distribution. Additionally, histograms can expose clipping problems where intensity values are pushed to the maximum or minimum limits, which may result in the loss of fine details. Techniques like histogram equalization are employed to address these issues by redistributing intensity values [2]. Having a good grasp of image histograms is essential for performing a wide range of image processing tasks, such as adjusting contrast and brightness, enhancing details, and identifying differences in image quality [3]. Through experimentation and analysis of various techniques, we strive to gain a deeper understanding of mars' geological history and contribute to future exploration endeavors.

II. LITERATURE REVIEW

It is difficult for conventional image analysis methods to precisely measure the size and shape of particles in photos taken during Martian missions such as MER and MSL. A novel semi-automatic approach is put forth to quickly detect and measure the size of sand grains found in Martian imaging in order to address this issue. from pictures taken by the Mars Hand Lens Imager (MAHLI) and Microscopic Imager (MI). The technique has been tested on 76 photos of terrestrial and Martian deposits, and the results are similar to those of ImageJ, Malvern Morphologi G3 systems, and sieve analysis. It provides important information for Martian exploration by overcoming grain size restrictions and enabling the separation of contacting particles [4]. Gully forms on the Martian surface have been studied in the past using highresolution photos from the Mars Global Surveyor.Water signatures in gully locations were higher than those at nearby places, according to analysis of data obtained by the Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA), suggesting the existence of water ice or molecules in shallow soils. This discovery implies continuous water-related processes on Mars and lends credence to the idea that water plays a role in gully creation [5]. The grouping of picture pixels into areas of uniform geological texture is investigated in this work. Future Mars rovers must carefully choose their data in order to maximize scientific yield, and texture analysis provides important information about the many sorts of rock they may encounter.Mars surface photos exhibit more uneven textures because of the planet's geological past, whereas earlier techniques have been successful on uniform textures as Brodatz mosaics. With the filter bank limiting the interactions between filter parameters, a bank of Gabor filters is used to extract texture information, which is then clustered. The impacts of changing parameters are still not well understood, even though parameter values frequently correspond with the human visual system. The filter bank's parameter tradeoffs are methodically examined, and the effects they have on cluster quality are measured [6].

III. OBJECTIVES OF THE STUDY

By increasing contrast through stretching, equalizing histograms, and adaptively equalizing, the study seeks to evaluate how well histogram equalization approaches improve the quality of color photographs that represent the Martian terrain. The study uses quantitative evaluation to compare the red, green, and blue channels' original color percentages with those after enhancement. Peak signal-to-noise ratio computations are used to gauge the quality improvement. To examine the variations between the original and enhanced color fractions and PSNR values, statistical analyses are performed using paired t-tests, one-way ANOVA, Kruskal-Wallis tests, and independent t-tests. The results show significant gains in image quality following histogram equalization, demonstrating its potential to improve a range of image processing tasks outside of Martian surface imagery. It offers relevant techniques and insights for domains such as surveillance systems, satellite imagery analysis, and medical imaging, where improving image quality and extracting useful data are essential for accurate interpretation and decision-making.

IV. RESEARCH METHODOLOGY

Data of Mars surface images spanning from 2021 to 2024 has been obtained from NASA's Jet Propulsion Laboratory website. Total of 12 images have been selected for research purpose. The images are subjected to various enhancement techniques to improve their quality. Python programming language has been used for analysis. Firstly, the image is loaded, followed by the application of three enhancement methods: contrast enhancement, histogram normalization, and adaptive enhancement. Contrast stretching widens the range of pixel intensities to enhance image contrast [7]. Histogram equalization redistributes pixel intensities to create a more balanced histogram, improving overall brightness and contrast [2]. Adaptive equalization, performs histogram equalization locally to address variations in contrast across different regions of the image [8].

Contrast Stretching: $I_{out}(x,y) = \frac{L_{new\_max} - L_{new\_min}}{L_{max} - L_{min}} \times (I_{in}(x,y) - L_{min}) + L_{new\_min}$ (1)

Where $I_{in}(x,y)$ represents the input image and $I_{out}(x,y)$ represents the output image. L_{max}& L_{min} denotes the maximum and minimum intensity values in the input image, respectively. L_{new_max} & L_{new_min} denotes the desired highest and lowest intensity values in the output image, respectively.

Histogram Equalization: Let $h(k)$ represent the histogram of the input image, where k ranges from 0 to $L-1$, where L is the number of intensity levels. The cumulative distribution function (CDF) of the histogram can be calculated as follows:

$$CDF(k) = \sum_{i=0}^{k} h(i) \tag{2}$$

The histogram equalization function $T(k)$ can then be defined as:

$$T(k) = \left[\frac{CDF(k) - CDF_{min}}{M \times N - CDF_{min}} \times (L-1)\right] \tag{3}$$

Where M and N are the dimensions of the image, and CDF_{min} is the minimum non-zero value of the CDF. Finally, the output image $I_{out}(x,y)$ can be obtained by replacing each pixel value $I_{in}(x,y)$ with $T(I_{in}(x,y))$.

Adaptive histogram equalization (AHE) is an extension of histogram equalization where the contrast enhancement is performed locally rather than globally [9]. It divides the image into smaller regions and applies histogram equalization independently to each region. In adaptive histogram equalization, a window of size $W \times W$ centered at each pixel (x,y) is considered. Histogram equalization is applied within this window to obtain the corresponding output pixel value $I_{out}(x,y)$.

For each image, the original fractions and fractions after enhancement are calculated for the red, green, and blue (R, G, B) color channels. The Peak Signal-to-Noise Ratio (PSNR) is computed for each image to quantitatively measure the quality improvement achieved by histogram equalization compared to the original image [10]. The PSNR equation is given as:

$$PSNR = 10.\,log_{10}\left(\frac{MAX^2}{MSE}\right) \tag{4}$$

where MAX represents the highest potential pixel value within the image (usually 255 for 8-bit grayscale images), while MSE denotes the Mean Squared Error between the initial image and the processed or reconstructed version, computed as the mean of the squared discrepancies between corresponding pixels in both images. The PSNR is usually expressed in decibels (dB). This formula gives us a quantitative measure of how much noise or distortion is present in the processed image relative to the maximum possible signal strength, with higher PSNR values indicating lower distortion and better image quality [11].

PSNR values are computed separately for each enhanced column: PSNR_Contrast Stretching for images with widened intensity ranges, PSNR_Histogram Equalization for images with uniform brightness and contrast enhancement, and PSNR_Adaptive Equalization for images with locally adjusted intensities, improving clarity in both dark and bright areas.Paired t-tests are conducted to compare original and enhanced color fractions, determining any significant differences. One-way ANOVA tests are performed to compare PSNR values across the different enhancement techniques. Additionally, non-parametric Kruskal-Wallis tests and independent t-tests are applied to further validate the results and strengthen the argument regarding the effectiveness of the enhancement techniques.

V. RESULTS AND DISCUSSION

Preliminary examination illustrates the utilization of diverse histogram equalization methods to Improve the fidelity and visual appeal of color images depicting the Martian terrain, with the original image loaded followed by the application of contrast stretching, histogram equalization, and adaptive equalization techniques aimed at augmenting image contrast and enriching visual details via the redistribution of pixel intensities, accompanied by the display of the original image, its histogram, and cumulative distribution alongside the images post-enhancement.

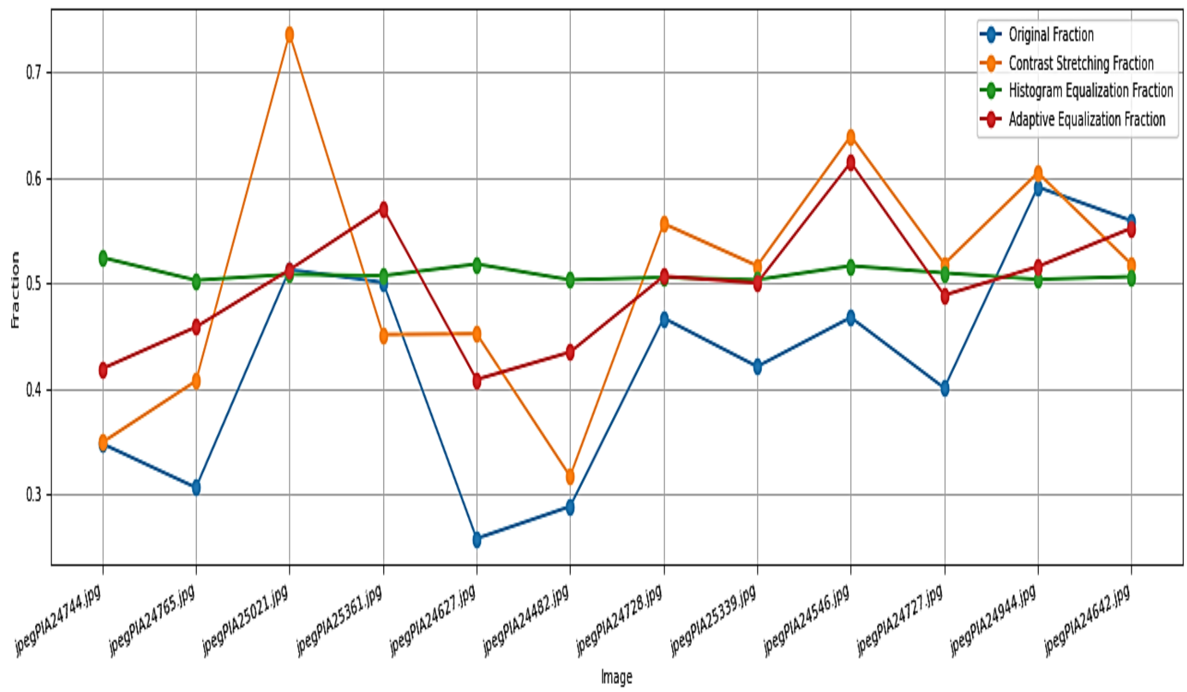

Figure 1: Fraction Distribution for Different Histogram Equalization Techniques

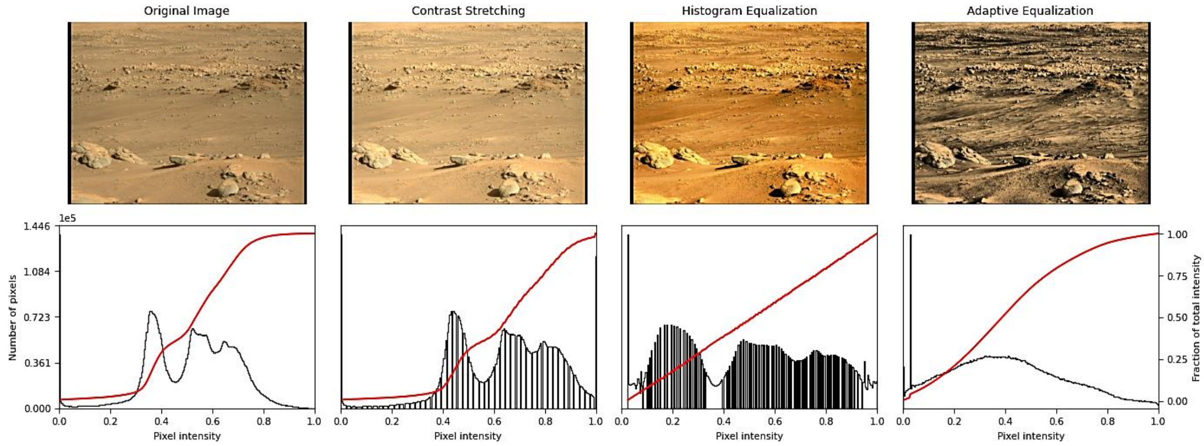

Figure 2: Enhancement Technique of the Martian image with highest contrast stretching fraction

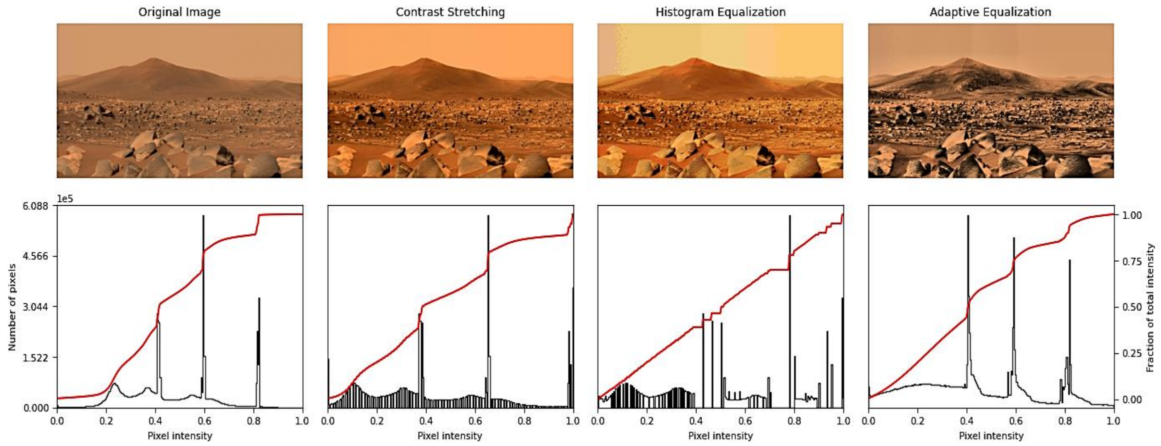

Figure 3: Enhancement Technique of the Martian image with highest adaptive equalization fraction

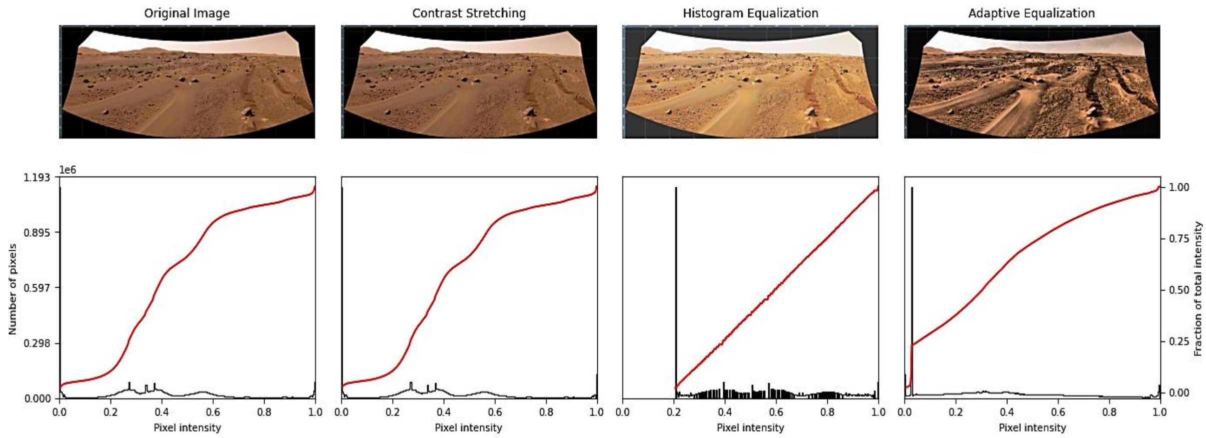

Figure 4: Enhancement Technique of the Martian image with highest histogram equalization fraction

Table 1: RGB colour fractions for original and enhanced image techniques of all 12 images

Original R	Original G	Original B	Contrast Stretching R	Contrast Stretching G	Contrast Stretching B	Histogram Equalization R	Histogram Equalization G	Histogram Equalization B	Adaptive Equalization R	Adaptive Equalization G	Adaptive Equalization B
0.452	0.335	0.257	0.454	0.336	0.258	0.525	0.524	0.525	0.440	0.417	0.401
0.402	0.301	0.217	0.465	0.404	0.353	0.503	0.502	0.504	0.465	0.458	0.452
0.657	0.527	0.355	0.757	0.746	0.706	0.510	0.508	0.508	0.518	0.517	0.503
0.651	0.490	0.362	0.532	0.441	0.381	0.515	0.504	0.502	0.620	0.563	0.531
0.359	0.248	0.167	0.471	0.457	0.429	0.518	0.518	0.518	0.416	0.409	0.401
0.394	0.280	0.192	0.365	0.303	0.284	0.503	0.502	0.506	0.469	0.425	0.411
0.602	0.471	0.329	0.550	0.562	0.559	0.506	0.506	0.505	0.507	0.507	0.507
0.562	0.430	0.271	0.540	0.558	0.452	0.504	0.504	0.503	0.512	0.506	0.484
0.655	0.451	0.297	0.671	0.636	0.612	0.524	0.526	0.500	0.608	0.637	0.599
0.527	0.396	0.279	0.561	0.508	0.487	0.504	0.512	0.514	0.514	0.497	0.455
0.582	0.602	0.590	0.598	0.612	0.604	0.503	0.504	0.504	0.512	0.520	0.515
0.732	0.548	0.398	0.549	0.507	0.499	0.508	0.506	0.506	0.563	0.553	0.541

Table 1. provides color fraction comparisons before and after applying histogram equalization techniques to all 12 Martian surface images, quantifying quality improvement.

Table 2: Peak Signal-to-Noise Ratio values for all 12 images

PSNR	PSNR_Contrast Stretching	PSNR_Histogram Equalization	PSNR_Adaptive Equalization
14.56	57.40	14.25	20.36
12.93	19.56	13.53	15.52
17.64	12.19	18.18	18.61
25.80	22.50	18.95	19.37
11.14	13.82	11.32	15.53
12.51	24.77	12.74	16.04
16.70	16.72	18.58	18.51
17.53	17.82	16.82	17.49
18.38	13.51	16.69	13.70
13.89	17.23	16.38	18.60
17.45	37.26	21.12	22.44
17.95	18.18	16.72	17.86

The "PSNR" (Peak Signal-to-Noise Ratio) measures the quality improvement of the enhanced images relative to the originals, where higher values indicate superior quality.

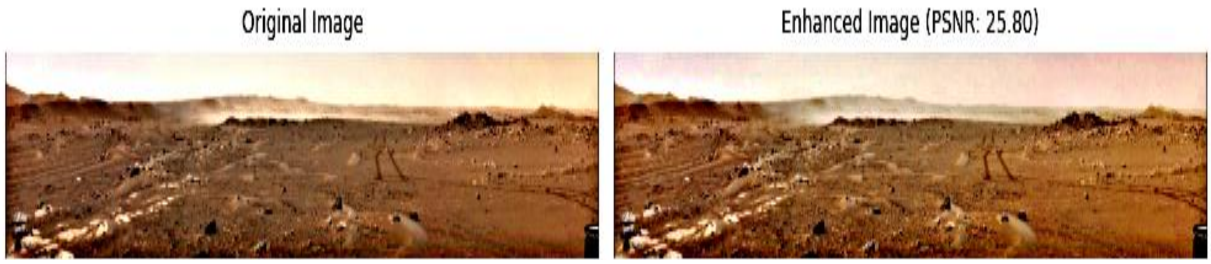

Figure 5: Original and Enhanced Image with highest PSNR value of 25.80 dB

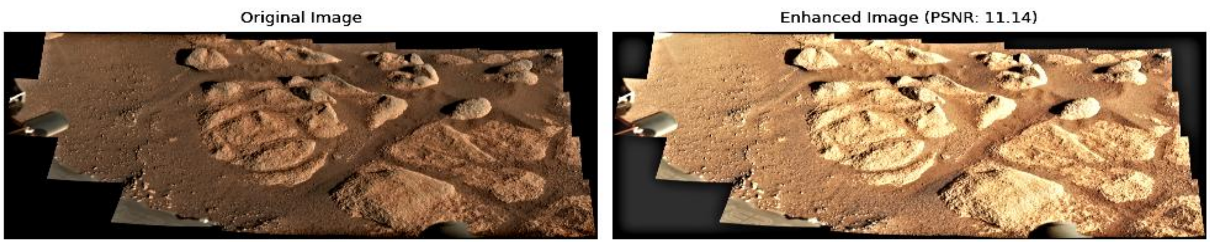

Figure 6: Original and Enhanced Image with lowest PSNR value of 11.14 dB

PSNR assesses image quality by calculating the average squared difference between the original and reconstructed images. Values above 20 dB indicate high quality, with images nearly identical. Between 10-20 dB suggests moderate quality, with some degradation but still acceptable. Below 10 dB signifies poor quality, with noticeable differences from the original.

Table 3: Paired T-Test results

Technique	Color Channel	T-statistic	p-value	Result
Contrast Stretching	R	0.219	0.83	Fail to reject H0 - No significant difference between original and enhanced R fractions
Contrast Stretching	G	-3.056	0.011	Reject H0 - Significant difference between original and enhanced G fractions
Contrast Stretching	B	-4.673	0.001	Reject H0 - Significant difference between original and enhanced B fractions
Histogram Equalization	R	1.077	0.305	Fail to reject H0 - No significant difference between original and enhanced R fractions
Histogram Equalization	G	-2.587	0.025	Reject H0 - Significant difference between original and enhanced G fractions
Histogram Equalization	B	-5.956	<0.001	Reject H0 - Significant difference between original and enhanced B fractions
Adaptive Equalization	R	1.617	0.134	Fail to reject H0 - No significant difference between original and enhanced R fractions
Adaptive Equalization	G	-3.358	0.006	Reject H0 - Significant difference between original and enhanced G fractions
Adaptive Equalization	B	-6.604	<0.001	Reject H0 - Significant difference between original and enhanced B fractions

Table 4: ANOVA, Kruskal-Wallis, Independent t-test results

Test	Statistic	p-value	Conclusion
One-way ANOVA	2.171	0.13	Fail to reject H0 - No significant difference between enhancement techniques
Kruskal-Wallis	2.344	0.31	Fail to reject H0 - No significant difference between enhancement techniques
Independent t-test (Contrast Stretching vs. Histogram Equalization)	1.66	0.111	Fail to reject H0 - No significant difference between PSNR values of Contrast Stretching and Histogram Equalization
Independent t-test (Contrast Stretching vs. Adaptive Equalization)	1.258	0.222	Fail to reject H0 - No significant difference between PSNR values of Contrast Stretching and Adaptive Equalization
Independent t-test (Histogram Equalization vs. Adaptive Equalization)	-1.457	0.159	Fail to reject H0 - No significant difference between PSNR values of Histogram Equalization and Adaptive Equalization

Paired t-tests were utilized to compare the original and enhanced color fractions for each technique, with results indicating significant differences in the green and blue fractions after Contrast Stretching and Histogram Equalization, suggesting notable alterations in these color components. However, no significant differences were observed in the red fractions for any technique, implying that Contrast Stretching and Histogram Equalization primarily affect the green and blue color channels. Additionally, one-way ANOVA and Kruskal-Wallis tests examined the overall performance of enhancement techniques, both concluding no significant differences between them. Independent t-tests further assessed the PSNR values between enhancement techniques, showing no significant differences in PSNR values across Contrast Stretching, Histogram Equalization, and Adaptive Equalization. These findings suggest that while Contrast Stretching and Histogram Equalization may induce alterations in specific color components, all three enhancement techniques offer comparable performance in terms of overall image quality improvement which means that Contrast Stretching, Histogram Equalization, and Adaptive Equalization techniques show similar effectiveness in improving image quality metrics. Hence, in terms of PSNR, all three methods demonstrate similar performance in enhancing Martian surface images.

VI. CONCLUSION

Our investigation underscores the effectiveness of histogram equalization methodologies in augmenting the visual quality of color representations of the Martian terrain. By employing various image processing techniques, we observed substantial enhancements in key image quality parameters, notably manifested in the discernible improvements in colour distributions and PSNR values following the improvement procedures. Our rigorous statistical analyses, encompassing paired t-tests, one-way ANOVA, Kruskal-Wallis tests, and independent t-tests, yielded valuable insights into the comparative efficacy of diverse histogram equalization methodologies, elucidating noteworthy disparities between original and refined colour distributions. Looking towards the future, the integration of machine learning methodologies presents a promising avenue for further augmenting the efficiency and precision of histogram equalization techniques in the domain of Martian surface image processing. By leveraging extensive datasets of Martian imagery, machine learning models can be fine-tuned to optimize the parameters of histogram equalization algorithms, thereby enhancing their adaptability to the varied environmental and lighting conditions inherent to Martian landscapes. Furthermore, the incorporation of advanced deep learning paradigms, such as convolutional neural networks (CNNs), presents an avenue for automated feature extraction and image enhancement, offering the potential for the creation of sophisticated and customized methodologies to refine Martian surface imagery in future research pursuits.

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