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### System and methods for low-light image enhancement utilizing denoising preprocessing with wavelet decomposition

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#### Abstract

A system and method are disclosed for adaptive low-light image enhancement using AI-based techniques and wavelet decomposition. The system analyzes characteristics of a raw input image, including brightness, contrast, noise levels, and detail complexity. Based on this analysis, an adaptation control subsystem determines optimal preprocessing parameters. These parameters guide an adaptive wavelet decomposition process, creating multiple frequency domain subimages. Each subimage is processed by a specialized neural network, tailored to its frequency range. The outputs of these networks are combined using an inverse wavelet transform, producing a denoised and enhanced image. This image then undergoes final processing in an image signal processing pipeline. The adaptive nature of the system allows for optimized enhancement across a wide range of low-light conditions, effectively balancing noise reduction, detail preservation, and overall image quality improvement.

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## Background/Summary

### CROSS-REFERENCE TO RELATED APPLICATIONS

(1) Priority is claimed in the application data sheet to the following patents or patent applications, each of which is expressly incorporated herein by reference in its entirety: Ser. No. 18/624,038

### BACKGROUND OF THE INVENTION

#### Field of the Art

(2) The present invention is in the field of image processing, and more particularly is directed to the problem of low-light image enhancement.

#### Discussion of the State of the Art

(3) Low-light digital images, such as those captured in challenging lighting conditions, can suffer from several disadvantages compared to images captured in well-lit conditions. One issue that is faced with low-light images is that of noise. Low-light images often have higher levels of noise, which can manifest as graininess or speckles in the image. This is due to the amplification of the sensor signal to compensate for the low light, which also amplifies the sensor's inherent noise. Another prevalent problem is loss of detail. In low-light conditions, the camera may struggle to capture fine details, leading to a loss of sharpness and clarity in the image. This can be exacerbated by some noise reduction algorithms, which may blur the image to reduce noise. Another issue that may occur is color distortion. Colors in low-light images can appear distorted or inaccurate due to the limited amount of light available for the sensor to capture. This can result in a lack of vibrancy and fidelity in the colors of the image. Moreover, low-light images can suffer from reduced dynamic range, meaning that there is less contrast between the darkest and lightest parts of the image. This can result in loss of detail in shadowed areas and highlights. Additionally, in low-light conditions, the camera may use longer exposure times to capture enough light, which can result in motion blur if there is any movement in the scene or if the camera is not held steady.

(4) Moreover, due to the challenges of capturing images in low-light conditions, low-light images may exhibit more digital artifacts, such as color noise, banding, posterization, or compression artifacts, especially when the image is processed or compressed. Color noise refers to random variations in color in an image, often seen as splotches or patches of unnatural colors. It can be more pronounced in low-light images due to the limited amount of light available for the sensor to capture. Banding may appear as visible bands of different shades or colors in an image, usually due to limitations in bit depth or compression. In low-light images, banding can be more noticeable, especially in areas of smooth gradient transitions. Posterization can occur when there are abrupt changes in color or tone in an image, resulting in a loss of smooth transitions. In low-light images, posterization can be more pronounced, particularly in areas with gradual changes in brightness or color. The aforementioned artifacts can impact the overall quality and appearance of low-light images. Overall, capturing high-quality images in low-light conditions can be challenging due to these disadvantages.

### SUMMARY OF THE INVENTION

(5) Accordingly, there is disclosed herein, systems and methods for low-light image enhancement utilizing denoising preprocessing with wavelet decomposition. In a digital camera, under low-light conditions, the image sensor can suffer from a low signal-to-noise ratio. The result can be noisy images, as not enough photons are reaching the image sensor under the low-light conditions. Digital cameras may employ countermeasures for low-light, each with corresponding shortcomings. For example, a digital camera may enlarge the aperture of the camera to allow additional light to reach the image sensor, but enlarging the aperture can reduce the depth of field,

causing at least part of the image to appear out of focus. An additional countermeasure can include increasing the exposure time. While this technique enables additional light to reach the sensor, it also increases the probability of undesired motion blur. Another option is increasing the ISO. ISO in digital photography refers to the sensitivity of the camera's sensor to light. ISO is an acronym for the International Organization for Standardization, which sets the standards for camera sensitivity ratings. In the context of photography, ISO is used to describe the sensor's sensitivity to light. A lower ISO number (e.g., ISO 100) indicates low sensitivity to light, meaning that more light is needed to properly expose the image. A lower ISO number is typically used in bright conditions to avoid overexposure and to maintain image quality. A higher ISO number (e.g., ISO 1600 or higher) indicates higher sensitivity to light, meaning that less light is needed to properly expose the image. This is useful in low-light conditions where there is not enough ambient light to properly expose the image. However, increasing the ISO also increases the amount of digital noise in the image, which can reduce image quality and create undesirable effects.

(6) Disclosed embodiments address the aforementioned problems and shortcomings by performing denoising on the low-light image in the Bayer domain prior to inputting the image information into the ISP (Image Signal Processing) pipeline. Embodiments utilize adaptive wavelet decomposition to divide and conquer the problem by processing sensor field subimages utilizing separate corresponding neural networks. The adaptive wavelet decomposition can include analyzing the raw input image to determine image characteristics, determining preprocessing parameters based on these characteristics, and decomposing the input raw image into multiple low and high frequency subimages using the determined parameters. Denoising the image in this way prior to inputting the image data into the ISP can improve the efficacy of downstream processing in the ISP, thereby creating improved low-light images.

(7) According to a preferred embodiment, there is provided a system for image enhancement, comprising: a computing device comprising at least a memory and a processor; a denoising preprocessing subsystem comprising a first plurality of programming instructions stored in the memory and operable on the processor, wherein the first plurality of programming instructions, when operating on the processor, cause the computing device to: create a plurality of subsampled subimages from a raw input image; analyze the raw input image to determine image characteristics; determine preprocessing parameters based on the image characteristics; perform an adaptive wavelet decomposition process on each subimage from the plurality of subimages using the determined preprocessing parameters to generate a plurality of frequency domain subimages; input each frequency domain subimage from the plurality of frequency domain subimages into a corresponding neural network; provide an output of each corresponding neural network to an inverse wavelet subsystem; and provide an output of the inverse wavelet subsystem to an image signal processing pipeline.

(8) According to another preferred embodiment, there is provided a method for image enhancement, comprising steps of: creating a plurality of subsampled subimages from a raw input image; analyzing the raw input image to determine image characteristics; determining preprocessing parameters based on the image characteristics; performing an adaptive wavelet decomposition process on each subimage from the plurality of subimages using the determined preprocessing parameters to generate a plurality of frequency domain subimages; inputting each frequency domain subimage from the plurality of frequency domain subimages into a corresponding neural network; providing an output of each corresponding neural network to an inverse wavelet subsystem; and providing an output of the inverse wavelet subsystem to an image signal processing pipeline.

(9) According to another preferred embodiment, there is provided a computer program product for an electronic computation device comprising a computer readable storage medium having program instructions embodied therewith, the program instructions executable by a processor to cause the electronic computation device to: create a plurality of subsampled subimages from a raw input

image; analyze the raw input image to determine image characteristics; determine preprocessing parameters based on the image characteristics; perform an adaptive wavelet decomposition process on each subimage from the plurality of subimages using the determined preprocessing parameters to generate a plurality of frequency domain subimages; input each frequency domain subimage from the plurality of frequency domain subimages into a corresponding neural network; provide an output of each corresponding neural network to an inverse wavelet subsystem; and provide an output of the inverse wavelet subsystem to an image signal processing pipeline.

(10) According to an aspect of an embodiment, the denoising preprocessing module further comprises programming instructions stored in the memory and operable on the processor to create the plurality of subsampled subimages from a Bayer raw input image.

(11) According to an aspect of an embodiment, the denoising preprocessing module further comprises programming instructions stored in the memory and operable on the processor to select and utilize one of multiple wavelet types, including a Haar wavelet, as a decomposition filter in the adaptive wavelet decomposition process based on the determined preprocessing parameters.

(12) According to an aspect of an embodiment, the denoising preprocessing module further comprises programming instructions stored in the memory and operable on the processor to create a variable number of frequency domain subimages for the plurality of frequency domain subimages based on the determined preprocessing parameters.

(13) According to an aspect of an embodiment, the denoising preprocessing module further comprises programming instructions stored in the memory and operable on the processor to perform adaptive downsampling as part of the adaptive wavelet decomposition process based on the determined preprocessing parameters.

(14) According to an aspect of an embodiment, the denoising preprocessing module further comprises programming instructions stored in the memory and operable on the processor to perform processing rows of image data, followed by processing columns of image data.

(15) According to an aspect of an embodiment, there is provided a neural network module comprising a second plurality of programming instructions stored in the memory and operable on the processor to implement the plurality of neural networks, wherein each neural network includes a Leaky ReLU activation function.

(16) According to an aspect of an embodiment, the neural network module further comprises programming instructions stored in the memory and operable on the processor to implement a plurality of neural network blocks, wherein the plurality of neural network blocks includes at least one convolutional block, and least one residual block, and at least one Squeeze-and-Excitation block.

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## Description

### BRIEF DESCRIPTION OF THE DRAWING FIGURES

(1) FIG. 1 is a block diagram illustrating components for image enhancement utilizing a denoising preprocessing module, according to an embodiment.

(2) FIG. 2 is a block diagram illustrating an exemplary system architecture for image enhancement, according to an embodiment.

(3) FIG. 3 is a diagram indicating a wavelet transform architecture, according to an embodiment.

(4) FIG. 4 is a diagram indicating a neural network architecture, according to an embodiment.

(5) FIG. 5 is a diagram indicating additional details of the neural network architecture shown in FIG. 4, according to an embodiment.

(6) FIG. 6 shows an example of image enhancement performed by an embodiment.

(7) FIG. 7 is a method diagram illustrating an exemplary method for image enhancement utilizing a denoising preprocessing module, according to an embodiment.

(8) FIG. 8 illustrates an exemplary computing environment on which an embodiment described herein may be implemented, in full or in part.

(9) The drawings are not necessarily to scale. The drawings are merely schematic representations, not intended to portray specific parameters of the disclosed embodiments. The drawings are intended to depict only typical embodiments of the invention, and therefore should not be considered as limiting in scope.

#### DETAILED DESCRIPTION OF THE INVENTION

(10) Low-light digital images can be difficult to enhance. Underexposed images often have a limited dynamic range, meaning there is less contrast between the darkest and lightest areas of the image. This can result in a flat or dull appearance. Image signal processing (ISP) techniques, such as increasing the brightness of an underexposed image during the ISP pipeline can lead to an increase in digital noise, particularly in the darker areas. This can result in a grainy or speckled appearance, reducing image quality. Furthermore, underexposed areas of an image may lack detail and appear as solid black areas, especially in shadowed regions. This can result in a loss of important information and reduce the overall quality of the image.

(11) Disclosed embodiments address the aforementioned issues with a novel approach that includes denoising the input image prior to input to the ISP pipeline. Images in a Bayer RGBG format are subject to an adaptive wavelet decomposition process, resulting in multiple frequency domain subimages, where each frequency domain subimage represents a different frequency range of the original input image. The adaptive nature of the process allows for optimal handling of various low-light conditions and image characteristics.

(12) The adaptive preprocessing begins with an analysis of the raw input image to determine its characteristics. This analysis may include assessing overall brightness, contrast levels, noise estimation, and detail complexity. Based on these characteristics, preprocessing parameters are determined. These parameters guide the subsequent adaptive wavelet decomposition process.

(13) The adaptive wavelet decomposition process utilizes the determined preprocessing parameters to optimize its operation. This may involve selecting the most appropriate wavelet type from multiple options (including Haar wavelets) based on the image characteristics. The process can also adjust the number of frequency domain subimages generated and modify the downsampling approach as needed.

(14) Each resulting frequency domain subimage is then input to a corresponding neural network. The neural networks are trained on dark data sets with a corresponding noise-free ground truth image. Once trained, the neural networks can provide wavelet outputs that can then be input to an inverse wavelet process to produce a denoised image that is then input to the ISP pipeline. By denoising the image using one or more neural networks prior to the ISP pipeline, the ISP pipeline can achieve improved results in terms of extracting details from low-light images.

(15) Digital photography plays a significant role in today's society, influencing various aspects of our lives, including communication, entertainment, documentation, and art. Digital photography enables people to visually communicate ideas, emotions, and experiences quickly and easily. Platforms like social media and messaging apps rely heavily on images to convey messages and connect people around the world. Digital photography has revolutionized the way we document events, experiences, and history. It allows the capturing of moments in time and preserve them for future generations. From personal memories to historical events, digital photography plays a crucial role in documenting our lives. Digital photography is a powerful tool for journalism and storytelling, allowing journalists and storytellers to capture and convey powerful narratives through images.

(16) Beyond these important benefits, digital photography also plays a crucial role in security and criminal investigations, providing law enforcement agencies with valuable tools for capturing, analyzing, and documenting evidence. Digital photography is used in surveillance systems to monitor and record activities in public spaces, buildings, and other areas of interest. Surveillance

images can be used to identify suspects, track their movements, and gather evidence of criminal activity. Sometimes the images are acquired under lighting conditions that are less than ideal. The image processing techniques provided by disclosed embodiments can enable improved enhancement of low-light images, potentially revealing important evidence to law enforcement authorities.

(17) Digital image acquisition devices, whether they be security cameras, smartphone cameras, body cameras, or cameras for other applications, all share some common components and principles. The image sensor is a key component of a digital camera and is responsible for capturing light and converting it into digital signals. There are two main types of image sensors used in digital cameras: CCD (Charge-Coupled Device) and CMOS (Complementary Metal-Oxide-Semiconductor). The sensor's resolution, size, and sensitivity to light (ISO performance) are important factors in determining image quality. The image sensor receives focused light through a lens. The lens plays an important role in determining the sharpness, clarity, and depth of field of the final image. Different lenses have different focal lengths, apertures, and optical characteristics, allowing photographers to achieve various creative effects. Another important aspect of controlling how much light reaches the image sensor is the shutter. The shutter controls the duration of light exposure to the image sensor. When a digital image is acquired, the shutter opens to allow light to reach the sensor, and then closes to end the exposure. The shutter speed, measured in fractions of a second, determines how long the sensor is exposed to light and affects the motion blur in the image. Yet another aspect affecting how much light reaches the sensor is the aperture setting. The aperture is an adjustable opening in the lens that controls the amount of light passing through to the image sensor. It also affects the depth of field, or the range of distances over which objects appear sharp in the image. Aperture size is measured in f-stops, with smaller f-stop numbers indicating larger apertures and vice versa.

(18) The image sensor converts light into electrical signals, which are then processed to create a digital image. The sensor includes an array of light-sensitive pixels, each capable of converting light into an electrical signal. The image sensor may further include a Bayer filter array, which provides of a pattern of red, green, and blue filters placed over the pixels. Each pixel captures a color channel. After the digital image is captured, it undergoes further processing by an ISP (image signal processing) pipeline to enhance its quality and adjust factors such as brightness, contrast, and color balance. Disclosed embodiments provide adaptive preprocessing for the Bayer domain raw input image, and use adaptive wavelet decomposition to generate a denoised image that is then provided to the ISP pipeline, enabling improvements in extracting enhanced detail from low-light images.

(19) The adaptive nature of the preprocessing allows the system to handle a wide range of low-light conditions effectively. By analyzing the raw input image and determining appropriate preprocessing parameters, the system can optimize its processing for each specific image. This results in improved denoising and enhancement, particularly for challenging low-light scenarios where traditional methods may struggle.

(20) The ability to select from multiple wavelet types and adjust the number of frequency domain subimages provides flexibility in handling various image characteristics. For instance, images with fine details might benefit from a different wavelet type or decomposition level compared to images with larger, smoother areas. The adaptive downsampling further allows the system to preserve important details while effectively reducing noise.

(21) By implementing this adaptive approach, the disclosed embodiments can provide superior low-light image enhancement across a broader range of scenarios, from dimly lit indoor scenes to nighttime outdoor environments. This adaptability makes the system particularly valuable for applications like security and surveillance, where lighting conditions can vary dramatically and the ability to extract clear details from low-light images is crucial.

(22) One or more different aspects may be described in the present application. Further, for one or

more of the aspects described herein, numerous alternative arrangements may be described; it should be appreciated that these are presented for illustrative purposes only and are not limiting of the aspects contained herein or the claims presented herein in any way. One or more of the arrangements may be widely applicable to numerous aspects, as may be readily apparent from the disclosure. In general, arrangements are described in sufficient detail to enable those skilled in the art to practice one or more of the aspects, and it should be appreciated that other arrangements may be utilized and that structural, logical, software, electrical and other changes may be made without departing from the scope of the particular aspects. Particular features of one or more of the aspects described herein may be described with reference to one or more particular aspects or figures that form a part of the present disclosure, and in which are shown, by way of illustration, specific arrangements of one or more of the aspects. It should be appreciated, however, that such features are not limited to usage in the one or more particular aspects or figures with reference to which they are described. The present disclosure is neither a literal description of all arrangements of one or more of the aspects nor a listing of features of one or more of the aspects that must be present in all arrangements.

(23) Headings of sections provided in this patent application and the title of this patent application are for convenience only, and are not to be taken as limiting the disclosure in any way.

(24) Devices that are in communication with each other need not be in continuous communication with each other, unless expressly specified otherwise. In addition, devices that are in communication with each other may communicate directly or indirectly through one or more communication means or intermediaries, logical or physical.

(25) A description of an aspect with several components in communication with each other does not imply that all such components are required. To the contrary, a variety of optional components may be described to illustrate a wide variety of possible aspects and in order to more fully illustrate one or more aspects. Similarly, although process steps, method steps, algorithms or the like may be described in a sequential order, such processes, methods and algorithms may generally be configured to work in alternate orders, unless specifically stated to the contrary. In other words, any sequence or order of steps that may be described in this patent application does not, in and of itself, indicate a requirement that the steps be performed in that order. The steps of described processes may be performed in any order practical. Further, some steps may be performed simultaneously despite being described or implied as occurring non-simultaneously (e.g., because one step is described after the other step). Moreover, the illustration of a process by its depiction in a drawing does not imply that the illustrated process is exclusive of other variations and modifications thereto, does not imply that the illustrated process or any of its steps are necessary to one or more of the aspects, and does not imply that the illustrated process is preferred. Also, steps are generally described once per aspect, but this does not mean they must occur once, or that they may only occur once each time a process, method, or algorithm is carried out or executed. Some steps may be omitted in some aspects or some occurrences, or some steps may be executed more than once in a given aspect or occurrence.

(26) When a single device or article is described herein, it will be readily apparent that more than one device or article may be used in place of a single device or article. Similarly, where more than one device or article is described herein, it will be readily apparent that a single device or article may be used in place of the more than one device or article.

(27) The functionality or the features of a device may be alternatively embodied by one or more other devices that are not explicitly described as having such functionality or features. Thus, other aspects need not include the device itself.

(28) Techniques and mechanisms described or referenced herein will sometimes be described in singular form for clarity. However, it should be appreciated that particular aspects may include multiple iterations of a technique or multiple instantiations of a mechanism unless noted otherwise. Process descriptions or blocks in figures should be understood as representing modules, segments,



or portions of code which include one or more executable instructions for implementing specific logical functions or steps in the process. Alternate implementations are included within the scope of various aspects in which, for example, functions may be executed out of order from that shown or discussed, including substantially concurrently or in reverse order, depending on the functionality involved, as would be understood by those having ordinary skill in the art.

#### Definitions

(29) The term “bit” refers to the smallest unit of information that can be stored or transmitted. It is in the form of a binary digit (either 0 or 1). In terms of hardware, the bit is represented as an electrical signal that is either off (representing 0) or on (representing 1).

(30) The term “pixel” refers to the smallest controllable element of a digital image. It is a single point in a raster image, which is a grid of individual pixels that together form an image. Each pixel has its own color and brightness value, and when combined with other pixels, they create the visual representation of an image on a display device such as a computer monitor or a smartphone screen.

(31) The term “neural network” refers to a computer system modeled after the network of neurons found in a human brain. The neural network is composed of interconnected nodes, called artificial neurons or units, that work together to process complex information.

(32) The term “signal-to-noise ratio” (SNR) is a measure used in signal processing to quantify the ratio of the strength of a signal to the strength of background noise that affects the signal. A higher SNR indicates that the signal is stronger relative to the noise, which generally means that the signal is clearer and easier to detect or interpret. SNR may be expressed in decibels (dB) and is calculated as the ratio of the power of the signal to the power of the noise

(33) The term “Bayer RGBG format” refers to a color filter array for arranging RGB color filters on a square grid of photosensors, with green filters at opposing corners of each 2×2 unit cell, and red and blue filters in the other two positions.

(34) The term “wavelet decomposition” refers to a method of breaking down a signal (in this case, an image) into a set of wavelets of different scales and positions, allowing for analysis of both frequency and spatial information simultaneously.

(35) The term “frequency domain subimage” refers to an image representation that results from wavelet decomposition, where the image is divided into different frequency components.

(36) The term “adaptive wavelet decomposition” refers to a process where the parameters of wavelet decomposition (such as wavelet type and decomposition level) are dynamically adjusted based on the characteristics of the input image.

(37) The term “Image Signal Processing (ISP) pipeline” refers to a series of processing steps applied to raw image data from a camera sensor to produce a final, displayable image.

(38) The term “low-light image” refers to an image captured in conditions with insufficient illumination, typically resulting in high noise levels and loss of detail.

(39) The term “neural network” refers to a computational model inspired by biological neural networks, consisting of interconnected nodes (neurons) that process and transmit information.

(40) The term “Haar wavelet” refers to a sequence of rescaled “square-shaped” functions which together form a wavelet family or basis.

(41) The term “Daubechies wavelet” refers to a family of orthogonal wavelets characterized by a maximal number of vanishing moments for some given support.

(42) The term “Coiflet wavelet” refers to a discrete wavelet designed by Ingrid Daubechies to have scaling functions with vanishing moments.

(43) Conceptual Architecture

(44) FIG. 1 is a block diagram illustrating components for image enhancement utilizing a denoising preprocessing module, according to an embodiment. An image enhancement application **110** exists that comprises at least a denoising preprocessing module **112**, neural network module **114**, and inverse wavelet module **116**. The image enhancement application has connections to receive raw image source data **120**, and output data to the image signal processing (ISP) pipeline **160**. The raw

image source data **120** can include image source data in a Bayer format. A Bayer raw image is a type of image format that may be used in digital cameras and other imaging devices. The Bayer format may include images comprising multiple sets of four pixels. Each set includes a red pixel, a blue pixel, and two green pixels. This arrangement is based on the fact that the human eye is more sensitive to green light than to red or blue. One or more embodiments may utilize other formats as part of raw image source data **120**, instead of, or in addition to, data in a Bayer format. The raw image data can include bitmaps, tagged image file format (TIFF), and/or other raw formats such as NEF, ARW, RAF, RW2, and/or ORF formats.

(45) The denoising preprocessing module **112** can include functions and/or instructions for separating an image into low and high frequency components via digital filtering techniques, such as two-dimensional Fast Fourier Transforms (FFT), wavelet decomposition, and/or other suitable techniques. A combination of low-pass filtering, high-pass filtering, bandpass filtering, and/or notch filtering may be used to create multiple frequency domain subimages.

(46) The inverse wavelet module **116** accepts wavelet coefficients from a previous wavelet decomposition and reconstructs an original signal based on the coefficients. In one or more embodiments, a threshold may be used as a criterion for processing the wavelet coefficients in order to remove noise or small details, which can help in denoising the signal or image. The thresholded coefficients can be used to create a denoised version of the original signal or image using an inverse wavelet transform. The denoised image **150** is a denoised version of an image from the raw image source data **120**. Reconstructed image **150** is input to image signal processing (ISP) pipeline **160**. The ISP can include one or more processors and/or specialized circuits for processing the denoised image **150**. The ISP pipeline can include hardware and software for demosaicing, color correction, sharpening, tone mapping, and/or other functions. By denoising the image prior to inputting the image into the ISP pipeline **160**, disclosed embodiments can achieve improved enhancement of low-light images.

(47) FIG. 2 is a block diagram illustrating an exemplary system architecture for image enhancement, including an adaptive denoising preprocessing stage **202**, according to an embodiment. A raw image **210** is converted to a subsampled image **212** in a Bayer RGBG format, indicating an arrangement where a set of pixels includes a red pixel, a blue pixel, and two green pixels. The green pixels may be oriented diagonally from each other in one or more embodiments.

(48) The subsampled image is then input to image analysis subsystem **213**, which analyzes the image to determine its characteristics such as overall brightness, contrast levels, and noise estimation. The image analysis subsystem employs a suite of sophisticated algorithms to quantify various image properties. For overall brightness, it performs a weighted histogram analysis, calculating the average pixel intensity with higher weights given to mid-range values to avoid skew from extreme outliers. The resulting brightness score is normalized to a range of 0-1. Contrast levels are measured using both global and local approaches. Global contrast is computed using the root mean square (RMS) contrast method, while local contrast is assessed using a sliding window approach with Michelson contrast calculation. The final contrast metric combines these measures, weighted based on empirically determined importance factors.

(49) Noise estimation utilizes a wavelet-based technique, analyzing the high-frequency subbands of a discrete wavelet transform. The median absolute deviation (MAD) of the wavelet coefficients in these subbands provides a robust estimate of noise levels, which is then scaled to account for the specific characteristics of the imaging sensor. To quantify detail complexity, the subsystem applies Sobel edge detection to identify edge pixels, with the percentage of edge pixels providing a measure of image complexity. Additionally, a 2D Fourier transform is performed, and the energy distribution across different frequency bands is analyzed to further characterize image detail. The results of these analyses are combined into a feature vector, representing the image's characteristics in a multi-dimensional space. The results of this analysis are passed to an adaptation control subsystem **214**, which determines the optimal preprocessing parameters based on the image

characteristics.

(50) Adaptation control subsystem **214** employs a hybrid approach to determine the optimal preprocessing parameters. At its core is a gradient boosting decision tree (GBDT) model, trained on a diverse dataset of low-light images and their optimal preprocessing parameters. This model takes the feature vector as input and outputs initial estimates for the preprocessing parameters. These initial estimates are then refined by a rule-based system that applies domain-specific knowledge. This subsystem **214** includes rules based on established image processing principles and empirical observations from extensive testing. The preprocessing parameters include the wavelet decomposition level, wavelet type selection, thresholding parameters, and subband weighting factors. The decomposition level is adjusted based on the detail complexity and noise levels, with higher complexity and lower noise typically warranting more decomposition levels. For wavelet type selection, the system chooses between Haar, Daubechies (Db4), and Coiflet (Coif3) wavelets. Haar wavelets are selected for images with sharp transitions, Db4 for smoother images with moderate detail, and Coif3 for images with fine, complex textures. Thresholding parameters, which control the denoising strength in each subband, are primarily influenced by the estimated noise level and contrast of the image. Higher noise levels result in more aggressive thresholding, while higher contrast allows for more conservative thresholding to preserve details. Subband weighting factors determine the relative importance of each frequency subband in the reconstruction process. They are adjusted based on the image's brightness and detail complexity, with darker images with high complexity receiving higher weights for high-frequency subbands to preserve details.

(51) Adaptation control subsystem **214** uses these parameters to configure the adaptive wavelet decomposition subsystem **215**. This dynamic configuration ensures that the wavelet decomposition process is optimized for each specific input image, allowing the system to effectively handle a wide range of low-light conditions and image types.

(52) Adaptive wavelet decomposition subsystem **215** creates multiple frequency domain subimages. The adaptive wavelet decomposition process incorporates several key features to optimize its performance for various types of low-light images. The system dynamically selects the most appropriate wavelet type based on the image characteristics determined by the image analysis subsystem. The selection criteria include edge characteristics, texture complexity, and the presence of smooth gradients. For images with sharp, well-defined edges, as determined by edge detection algorithms, the system preferentially selects Haar wavelets due to their ability to preserve sharp transitions. Images with complex textures, identified through frequency analysis, are processed using Daubechies (Db4) wavelets, which offer a good balance between frequency localization and smoothness. For images dominated by smooth intensity transitions, the system opts for Coiflet (Coif3) wavelets, which provide higher-order vanishing moments and better handling of polynomial behavior in the image. The selection is made using a weighted scoring system that considers these factors, with the highest-scoring wavelet type being chosen for the decomposition.

(53) The number of subimages created can also vary based on the determined preprocessing parameters. Typically, four subimages are created via high-pass and low-pass filtering, denoted as LL, LH, HL, and HH. Each image represents a different frequency range. In embodiments, LL represents the lowest frequency range, HH represents the highest frequency range, and LH and HL represent intermediate ranges, where HL represents higher frequencies than the LH range. Each frequency domain subimage is then input to a corresponding neural network (**216**, **218**, **220**, **222**). These neural networks are specifically designed and trained for denoising tasks in different frequency ranges. Each network employs a convolutional architecture, which is particularly effective for image processing tasks. The networks include multiple convolutional layers, residual blocks for improved gradient flow, and Squeeze-and-Excitation blocks to adaptively recalibrate channel-wise feature responses.

(54) A key feature of these neural networks is the use of a Leaky ReLU activation function, which helps prevent the “dying ReLU” problem and allows for more nuanced handling of negative values,

which can be important in the context of frequency domain representations. The networks are trained on a large dataset of low-light images paired with their corresponding well-lit, noise-free ground truth images. This dataset includes a wide variety of scenes and lighting conditions to ensure robust performance.

(55) The training process involves minimizing a loss function that combines mean squared error (for overall reconstruction accuracy) with perceptual loss terms (to preserve important image features and textures). The networks are trained using a combination of synthetic low-light data (created by artificially darkening and adding noise to clean images) and real-world low-light photographs paired with long-exposure ground truth images. This diverse training data helps the networks generalize well to various real-world low-light scenarios.

(56) The LL frequency domain subimage is input to neural network **216**, the LH frequency domain subimage to neural network **218**, the HL frequency domain subimage to neural network **220**, and the HH frequency domain subimage to neural network **222**. Each network is specialized for its specific frequency range, allowing for optimal denoising performance across different scales and orientations of image features.

(57) The processed frequency domain subimages from these neural networks are then input to inverse wavelet module **224**, which reconstructs the denoised image. This denoised output is then fed into an image signal processing (ISP) pipeline **226**. The ISP pipeline **226** can then operate on this cleaner, denoised input image, applying further enhancements and adjustments to produce the final enhanced low-light image **228**.

(58) The adaptive nature of this preprocessing stage, combined with the specialized neural networks, allows the system to optimize its denoising process for each specific input image, resulting in improved performance across a wide range of low-light conditions. This approach is particularly effective because it combines the power of wavelet analysis for separating different scales of image features with the learning capabilities of neural networks, all within an adaptive framework that can adjust to the specific characteristics of each input image.

(59) In a non-limiting use case example of this system, consider a scenario where a user captures a photograph of a city street at night using a smartphone camera. The resulting image is underexposed due to the low-light conditions, with visible noise and loss of detail in shadow areas. As the raw image **210** in Bayer RGBG format enters the system, the image analysis subsystem **213** examines it, determining that it has very low overall brightness, moderate global contrast with low local contrast in shadow areas, high noise levels (particularly in darker regions), and moderate detail complexity with sharp edges from street lights and building outlines but low detail in shadowed areas. Based on this analysis, the adaptation control subsystem **214** sets the preprocessing parameters: a 3-level wavelet decomposition using Daubechies (Db4) wavelets, aggressive thresholding for high-frequency subbands to reduce noise, and higher weights assigned to mid-frequency subbands to preserve edge details while suppressing noise.

(60) The image then undergoes adaptive wavelet decomposition in subsystem **215** using these parameters, resulting in multiple frequency domain subimages. Each of these subimages is processed by its corresponding neural network (**216**, **218**, **220**, **222**): the low-frequency (LL) subimage is processed by network **216** to enhance overall brightness and contrast, the mid-frequency (LH and HL) subimages are enhanced by networks **218** and **220** for edge details and local contrast, and the high-frequency (HH) subimage undergoes more aggressive denoising in network **222**. Following this, the processed subimages are recombined using the inverse wavelet module **224**, resulting in a cleaner, more detailed image. This reconstructed image then passes through the ISP pipeline **226** for final adjustments, including color correction to account for the nighttime lighting conditions, further contrast enhancement to bring out details in shadow areas, and sharpening to accentuate fine details revealed by the denoising process.

(61) The final output **228** is an enhanced version of the nighttime street scene with significantly improved overall brightness, revealing details that were previously hidden in shadows. Noise is

substantially reduced, particularly in darker areas of the image, while edge details of buildings, street signs, and other urban features are more clearly defined. Importantly, despite the significant enhancement, the image maintains a natural look, avoiding an over-processed appearance. This use case demonstrates how the system's adaptive nature allows it to tailor its processing to the specific challenges of a nighttime urban scene, effectively balancing noise reduction, detail enhancement, and overall image improvement.

(62) FIG. 3 is a diagram indicating a wavelet transform architecture, according to an embodiment. In embodiments, a Bayer raw image **302** is input to a filter **304**, that produces a low frequency subimage and a high frequency subimage. In one or more embodiments, creating subsampled subimages from the raw input image comprises inputting a raw image in a Bayer raw image format. The low frequency subimage is input to downsampling module **310**, and the high frequency subimage is input to downsampling module **312**. In one or more embodiments, the downsampling performed by the downsampling modules can include a process of reducing the resolution of an image or subimage by removing pixels. In embodiments, the downsampling modules downsample by two. In one or more embodiments, the wavelet decomposition process further comprises downsampling. The output of downsampling module **310** is input to filter **314**, where the filter **314** produces a low frequency subimage and a high frequency subimage. A similar process occurs with the output of downsampling module **312**, which is input to filter **316**, where the filter **316** produces a low frequency subimage and a high frequency subimage. These images are again downsampled using respective downsampling modules **318**, **320**, **332**, and **334**. The resulting output are the frequency domain subimages, indicated as LL **322**, LH **324**, HL **336**, and HH **338**. In some embodiments, the filtering may be along rows of an image, columns of an image, diagonally, and/or other suitable technique. Embodiments can include processing rows of image data, followed by processing columns of image data.

(63) FIG. 4 is a diagram indicating a neural network architecture, according to an embodiment. The neural network architecture can include a convolutional layer **402**, the output of which feeds into residual block **404**, which then feeds into residual block **406**. The output of residual block **406** can feed into the output of SE (Squeeze-and-Excitation) block **407**. The SE block includes two main operations: squeeze and excitation. The squeeze operation involves reducing the spatial dimensions of the input feature maps to a single global value per channel. In embodiments, the squeeze operation is performed using global average pooling, which computes the average value of each channel across all spatial locations. The result is a 1D tensor with the same number of channels as the input. In the excitation operation, the 1D tensor obtained from the squeeze operation is passed through two fully connected (FC) layers with a non-linear activation function (such as the ReLU) in between. The first FC layer reduces the dimensionality of the tensor, while the second FC layer expands it back to the original number of channels. In embodiments, a sigmoid or softmax activation function is applied at the end to generate a channel-wise attention vector.

(64) In embodiments, the output of the excitation operation is multiplied element-wise with the input feature maps to recalibrate them. This operation scales the feature maps by the importance assigned to each channel by the excitation operation. By incorporating the SE block into disclosed embodiments, the network can learn to selectively emphasize informative features and suppress irrelevant ones for the purposes of denoising an image, leading to improved accuracy and efficiency in enhancement of low-light images.

(65) The output of the SE block **407** is input to another convolutional layer **408**. The network continues to combiner **421** where the output of the convolutional layer **408** is combined with the output of convolutional layer **402**, and is provided as input to convolutional layer **420**, followed by shuffle layer **422**, and additional convolutional layer **424**. The neural network architecture of FIG. 4 is exemplary, and other embodiments may have more, fewer, and/or different components. For example, while two residual blocks are shown in FIG. 4, other embodiments may have more or fewer residual blocks.

(66) In embodiments, the shuffle layer can be used to introduce some form of permutation or rearrangement into the data flow of a neural network, which can help improve the network's ability to learn complex patterns and relationships in the data for the purposes of denoising an image. In embodiments, the residual blocks can serve to address the problem of vanishing gradients in deep networks by introducing skip connections that allow the gradient to flow more directly through the network.

(67) FIG. 5 is a diagram indicating additional details of the neural network architecture shown in FIG. 4, according to an embodiment. In particular, FIG. 5 shows additional details of a residual block such as shown at 404 in FIG. 4. The residual block includes a convolutional block 502. The convolutional block can include one or more convolutional layers. In embodiments, each convolutional layer/block includes a set of learnable filters (also known as kernels) are applied to the input data. Each filter is convolved with the input data to produce a feature map, which highlights the presence of particular patterns or features in the input. The convolution operation involves sliding the filter over the input data, performing element-wise multiplication and summing the results to produce a single value in the output feature map. The output of convolutional block 502 is fed to activation function 504. In one or more embodiments, the activation function 504 includes a non-linear activation function. In one or more embodiments, the activation function 504 includes a ReLU (Rectified Linear Unit). In one or more embodiments, the activation function 504 includes a Leaky ReLU (Rectified Linear Unit). The Leaky ReLU (Rectified Linear Unit) is a type of activation function used in artificial neural networks. It is similar to the standard ReLU function but allows a small, non-zero gradient when the input is negative, instead of setting the gradient to zero. In one or more embodiments, the Leaky ReLU activation function is defined as follows:

$$(68) f(x) = \begin{cases} x, & \text{if } x > 0 \\ \alpha x, & \text{otherwise} \end{cases}$$

(69) Where  $\alpha$  is a small constant, such as 0.01, that determines the slope of the function for negative inputs. This can serve to reduce the probability of developing inactive neurons during training and/or operational use of the neural network.

(70) The output of the activation function 504 can be input to another convolutional block 506. The output of convolutional block 506 can be fed to an additional activation function 508. In one or more embodiments, the activation function 508 can include a sigmoid function. The sigmoid function can be used to introduce non-linearity into the network. In one or more embodiments, the sigmoid function is defined as:

$$(71) f(x) = \frac{1}{1 + e^{-x}}$$

(72) Where  $e$  is the base of the natural logarithm. The sigmoid function has a characteristic S-shaped curve that maps any real value to a value between 0 and 1. This property makes it suitable for binary classification problems, where the output can be interpreted as the probability of the input belonging to a certain class, including the identification of noise and artifacts in images, in accordance with disclosed embodiments. In one or more embodiments, the activation function 508 can include a ReLU function instead of, or in addition to, the sigmoid function. Other embodiments can include a Tanh (hyperbolic tangent) activation function, softmax activation function, swish activation function, and/or other suitable activation function.

(73) FIG. 6 shows an example of image enhancement performed by an embodiment. Image 602 is a low-light image, containing minimal visible details. An area within the image 602, denoted by rectangle 603, is extracted as a raw input image, and processed using a system such as depicted in FIG. 2. The resulting enhanced low-light image is shown at 604. As can be seen, the enhanced low-light image reveals additional details not easily visible in the original image 602.

#### Detailed Description of Exemplary Aspects

(74) FIG. 7 is a method diagram illustrating an exemplary method 700 for image enhancement utilizing an adaptive denoising preprocessing module, according to an embodiment. The process

begins at step **701** where a raw input image **210** is received, typically in a Bayer RGBG format from a digital camera sensor. At step **702**, the image analysis subsystem **213** performs a comprehensive analysis of the input image, quantifying characteristics such as overall brightness, contrast levels, noise estimation, and detail complexity.

(75) At step **703**, the adaptation control subsystem **214** uses the analysis results to determine optimal preprocessing parameters. These parameters include the wavelet decomposition level, wavelet type selection, thresholding parameters, and subband weighting factors. At step **704**, adaptive wavelet decomposition **215** is performed using the determined parameters, resulting in multiple frequency domain subimages.

(76) At step **705**, the frequency domain subimages are input to corresponding neural networks **216**, **218**, **220**, and **222**. Each network is specialized for a specific frequency range (LL, LH, HL, HH) and applies denoising and enhancement techniques appropriate for that range. At step **706**, the output of the neural networks is provided to an inverse wavelet module **224**, which reconstructs the enhanced image from the processed frequency domain subimages.

(77) At step **707**, the reconstructed image is provided to an image signal processing (ISP) pipeline **226** for final adjustments. These may include color correction, further contrast enhancement, and sharpening. Finally, at step **708**, an enhanced low-light image **228** is produced as an output of the ISP pipeline, featuring improved brightness, reduced noise, and enhanced detail compared to the original input image.

(78) Exemplary Computing Environment

(79) FIG. **8** illustrates an exemplary computing environment on which an embodiment described herein may be implemented, in full or in part. This exemplary computing environment describes computer-related components and processes supporting enabling disclosure of computer-implemented embodiments. Inclusion in this exemplary computing environment of well-known processes and computer components, if any, is not a suggestion or admission that any embodiment is no more than an aggregation of such processes or components. Rather, implementation of an embodiment using processes and components described in this exemplary computing environment will involve programming or configuration of such processes and components resulting in a machine specially programmed or configured for such implementation. The exemplary computing environment described herein is only one example of such an environment and other configurations of the components and processes are possible, including other relationships between and among components, and/or absence of some processes or components described. Further, the exemplary computing environment described herein is not intended to suggest any limitation as to the scope of use or functionality of any embodiment implemented, in whole or in part, on components or processes described herein.

(80) The exemplary computing environment described herein comprises a computing device **10** (further comprising a system bus **11**, one or more processors **20**, a system memory **30**, one or more interfaces **40**, one or more non-volatile data storage devices **50**), external peripherals and accessories **60**, external communication devices **70**, remote computing devices **80**, and cloud-based services **90**.

(81) System bus **11** couples the various system components, coordinating operation of and data transmission between those various system components. System bus **11** represents one or more of any type or combination of types of wired or wireless bus structures including, but not limited to, memory busses or memory controllers, point-to-point connections, switching fabrics, peripheral busses, accelerated graphics ports, and local busses using any of a variety of bus architectures. By way of example, such architectures include, but are not limited to, Industry Standard Architecture (ISA) busses, Micro Channel Architecture (MCA) busses, Enhanced ISA (EISA) busses, Video Electronics Standards Association (VESA) local busses, a Peripheral Component Interconnects (PCI) busses also known as a Mezzanine busses, or any selection of, or combination of, such busses. Depending on the specific physical implementation, one or more of the processors **20**,

system memory **30** and other components of the computing device **10** can be physically co-located or integrated into a single physical component, such as on a single chip. In such a case, some or all of system bus **11** can be electrical pathways within a single chip structure.

(82) Computing device may further comprise externally-accessible data input and storage devices **12** such as compact disc read-only memory (CD-ROM) drives, digital versatile discs (DVD), or other optical disc storage for reading and/or writing optical discs **62**; magnetic cassettes, magnetic tape, magnetic disk storage, or other magnetic storage devices; or any other medium which can be used to store the desired content and which can be accessed by the computing device **10**.

Computing device may further comprise externally-accessible data ports or connections **12** such as serial ports, parallel ports, universal serial bus (USB) ports, and infrared ports and/or transmitter/receivers. Computing device may further comprise hardware for wireless communication with external devices such as IEEE 1394 (“Firewire”) interfaces, IEEE 802.11 wireless interfaces, BLUETOOTH® wireless interfaces, and so forth. Such ports and interfaces may be used to connect any number of external peripherals and accessories **60** such as visual displays, monitors, and touch-sensitive screens **61**, USB solid state memory data storage drives (commonly known as “flash drives” or “thumb drives”) **63**, printers **64**, pointers and manipulators such as mice **65**, keyboards **66**, and other devices **67** such as joysticks and gaming pads, touchpads, additional displays and monitors, and external hard drives (whether solid state or disc-based), microphones, speakers, cameras, and optical scanners.

(83) Processors **20** are logic circuitry capable of receiving programming instructions and processing (or executing) those instructions to perform computer operations such as retrieving data, storing data, and performing mathematical calculations. Processors **20** are not limited by the materials from which they are formed or the processing mechanisms employed therein, but are typically comprised of semiconductor materials into which many transistors are formed together into logic gates on a chip (i.e., an integrated circuit or IC). The term processor includes any device capable of receiving and processing instructions including, but not limited to, processors operating on the basis of quantum computing, optical computing, mechanical computing (e.g., using nanotechnology entities to transfer data), and so forth. Depending on configuration, computing device **10** may comprise more than one processor. For example, computing device **10** may comprise one or more central processing units (CPUs) **21**, each of which itself has multiple processors or multiple processing cores, each capable of independently or semi-independently processing programming instructions. Further, computing device **10** may comprise one or more specialized processors such as a graphics processing unit (GPU) **22** configured to accelerate processing of computer graphics and images via a large array of specialized processing cores arranged in parallel.

(84) System memory **30** is processor-accessible data storage in the form of volatile and/or nonvolatile memory. System memory **30** may be either or both of two types: non-volatile memory and volatile memory. Non-volatile memory **30a** is not erased when power to the memory is removed, and includes memory types such as read only memory (ROM), electronically-erasable programmable memory (EEPROM), and rewritable solid-state memory (commonly known as “flash memory”). Non-volatile memory **30a** is typically used for long-term storage of a basic input/output system (BIOS) **31**, containing the basic instructions, typically loaded during computer startup, for transfer of information between components within computing device, or a unified extensible firmware interface (UEFI), which is a modern replacement for BIOS that supports larger hard drives, faster boot times, more security features, and provides native support for graphics and mouse cursors. Non-volatile memory **30a** may also be used to store firmware comprising a complete operating system **35** and applications **36** for operating computer-controlled devices. The firmware approach is often used for purpose-specific computer-controlled devices such as appliances and Internet-of-Things (IoT) devices where processing power and data storage space is limited. Volatile memory **30b** is erased when power to the memory is removed and is typically used



for short-term storage of data for processing. Volatile memory **30b** includes memory types such as random-access memory (RAM), and is normally the primary operating memory into which the operating system **35**, applications **36**, program modules **37**, and application data **38** are loaded for execution by processors **20**. Volatile memory **30b** is generally faster than non-volatile memory **30a** due to its electrical characteristics and is directly accessible to processors **20** for processing of instructions and data storage and retrieval. Volatile memory **30b** may comprise one or more smaller cache memories which operate at a higher clock speed and are typically placed on the same IC as the processors to improve performance.

(85) Interfaces **40** may include, but are not limited to, storage media interfaces **41**, network interfaces **42**, display interfaces **43**, and input/output interfaces **44**. Storage media interface **41** provides the necessary hardware interface for loading data from non-volatile data storage devices **50** into system memory **30** and storage data from system memory **30** to non-volatile data storage device **50**. Network interface **42** provides the necessary hardware interface for computing device **10** to communicate with remote computing devices **80** and cloud-based services **90** via one or more external communication devices **70**. Display interface **43** allows for connection of displays **61**, monitors, touchscreens, and other visual input/output devices. Display interface **43** may include a graphics card for processing graphics-intensive calculations and for handling demanding display requirements. Typically, a graphics card includes a graphics processing unit (GPU) and video RAM (VRAM) to accelerate display of graphics. One or more input/output (I/O) interfaces **44** provide the necessary support for communications between computing device **10** and any external peripherals and accessories **60**. For wireless communications, the necessary radio-frequency hardware and firmware may be connected to I/O interface **44** or may be integrated into I/O interface **44**.

(86) Non-volatile data storage devices **50** are typically used for long-term storage of data. Data on non-volatile data storage devices **50** is not erased when power to the non-volatile data storage devices **50** is removed. Non-volatile data storage devices **50** may be implemented using any technology for non-volatile storage of content including, but not limited to, CD-ROM drives, digital versatile discs (DVD), or other optical disc storage; magnetic cassettes, magnetic tape, magnetic disc storage, or other magnetic storage devices; solid state memory technologies such as EEPROM or flash memory; or other memory technology or any other medium which can be used to store data without requiring power to retain the data after it is written. Non-volatile data storage devices **50** may be non-removable from computing device **10** as in the case of internal hard drives, removable from computing device **10** as in the case of external USB hard drives, or a combination thereof, but computing device will typically comprise one or more internal, non-removable hard drives using either magnetic disc or solid-state memory technology. Non-volatile data storage devices **50** may store any type of data including, but not limited to, an operating system **51** for providing low-level and mid-level functionality of computing device **10**, applications **52** for providing high-level functionality of computing device **10**, program modules **53** such as containerized programs or applications, or other modular content or modular programming, application data **54**, and databases **55** such as relational databases, non-relational databases, object oriented databases, BOSQL databases, and graph databases.

(87) Applications (also known as computer software or software applications) are sets of programming instructions designed to perform specific tasks or provide specific functionality on a computer or other computing devices. Applications are typically written in high-level programming languages such as C++, Java, and Python, which are then either interpreted at runtime or compiled into low-level, binary, processor-executable instructions operable on processors **20**. Applications may be containerized so that they can be run on any computer hardware running any known operating system. Containerization of computer software is a method of packaging and deploying applications along with their operating system dependencies into self-contained, isolated units known as containers. Containers provide a lightweight and consistent runtime environment that allows applications to run reliably across different computing environments, such as development,

testing, and production systems.

(88) The memories and non-volatile data storage devices described herein do not include communication media. Communication media are means of transmission of information such as modulated electromagnetic waves or modulated data signals configured to transmit, not store, information. By way of example, and not limitation, communication media includes wired communications such as sound signals transmitted to a speaker via a speaker wire, and wireless communications such as acoustic waves, radio frequency (RF) transmissions, infrared emissions, and other wireless media.

(89) External communication devices **70** are devices that facilitate communications between computing device and either remote computing devices **80**, or cloud-based services **90**, or both. External communication devices **70** include, but are not limited to, data modems **71** which facilitate data transmission between computing device and the Internet **75** via a common carrier such as a telephone company or internet service provider (ISP), routers **72** which facilitate data transmission between computing device and other devices, and switches **73** which provide direct data communications between devices on a network. Here, modem **71** is shown connecting computing device **10** to both remote computing devices **80** and cloud-based services **90** via the Internet **75**. While modem **71**, router **72**, and switch **73** are shown here as being connected to network interface **42**, many different network configurations using external communication devices **70** are possible. Using external communication devices **70**, networks may be configured as local area networks (LANs) for a single location, building, or campus, wide area networks (WANs) comprising data networks that extend over a larger geographical area, and virtual private networks (VPNs) which can be of any size but connect computers via encrypted communications over public networks such as the Internet **75**. As just one exemplary network configuration, network interface **42** may be connected to switch **73** which is connected to router **72** which is connected to modem **71** which provides access for computing device **10** to the Internet **75**. Further, any combination of wired **77** or wireless **76** communications between and among computing device **10**, external communication devices **70**, remote computing devices **80**, and cloud-based services **90** may be used. Remote computing devices **80**, for example, may communicate with computing device through a variety of communication channels **74** such as through switch **73** via a wired **77** connection, through router **72** via a wireless connection **76**, or through modem **71** via the Internet **75**. Furthermore, while not shown here, other hardware that is specifically designed for servers may be employed. For example, secure socket layer (SSL) acceleration cards can be used to offload SSL encryption computations, and transmission control protocol/internet protocol (TCP/IP) offload hardware and/or packet classifiers on network interfaces **42** may be installed and used at server devices.

(90) In a networked environment, certain components of computing device **10** may be fully or partially implemented on remote computing devices **80** or cloud-based services **90**. Data stored in non-volatile data storage device **50** may be received from, shared with, duplicated on, or offloaded to a non-volatile data storage device on one or more remote computing devices **80** or in a cloud computing service **92**. Processing by processors **20** may be received from, shared with, duplicated on, or offloaded to processors of one or more remote computing devices **80** or in a distributed computing service **93**. By way of example, data may reside on a cloud computing service **92**, but may be usable or otherwise accessible for use by computing device **10**. Also, certain processing subtasks may be sent to a microservice **91** for processing with the result being transmitted to computing device **10** for incorporation into a larger processing task. Also, while components and processes of the exemplary computing environment are illustrated herein as discrete units (e.g., OS **51** being stored on non-volatile data storage device **51** and loaded into system memory **35** for use) such processes and components may reside or be processed at various times in different components of computing device **10**, remote computing devices **80**, and/or cloud-based services **90**.

(91) In an implementation, the disclosed systems and methods may utilize, at least in part,

containerization techniques to execute one or more processes and/or steps disclosed herein.

Containerization is a lightweight and efficient virtualization technique that allows you to package and run applications and their dependencies in isolated environments called containers. One of the most popular containerization platforms is Docker, which is widely used in software development and deployment. Containerization, particularly with open-source technologies like Docker and container orchestration systems like Kubernetes, is a common approach for deploying and managing applications. Containers are created from images, which are lightweight, standalone, and executable packages that include application code, libraries, dependencies, and runtime. Images are often built from a Dockerfile or similar, which contains instructions for assembling the image. Dockerfiles are configuration files that specify how to build a Docker image. Systems like Kubernetes also support containers or CRI-O. They include commands for installing dependencies, copying files, setting environment variables, and defining runtime configurations. Docker images are stored in repositories, which can be public or private. Docker Hub is an exemplary public registry, and organizations often set up private registries for security and version control using tools such as Hub, JFrog Artifactory and Bintray, Github Packages or Container registries. Containers can communicate with each other and the external world through networking. Docker provides a bridge network by default, but can be used with custom networks. Containers within the same network can communicate using container names or IP addresses.

(92) Remote computing devices **80** are any computing devices not part of computing device **10**. Remote computing devices **80** include, but are not limited to, personal computers, server computers, thin clients, thick clients, personal digital assistants (PDAs), mobile telephones, watches, tablet computers, laptop computers, multiprocessor systems, microprocessor based systems, set-top boxes, programmable consumer electronics, video game machines, game consoles, portable or handheld gaming units, network terminals, desktop personal computers (PCs), minicomputers, main frame computers, network nodes, virtual reality or augmented reality devices and wearables, and distributed or multi-processing computing environments. While remote computing devices **80** are shown for clarity as being separate from cloud-based services **90**, cloud-based services **90** are implemented on collections of networked remote computing devices **80**.

(93) Cloud-based services **90** are Internet-accessible services implemented on collections of networked remote computing devices **80**. Cloud-based services are typically accessed via application programming interfaces (APIs) which are software interfaces which provide access to computing services within the cloud-based service via API calls, which are pre-defined protocols for requesting a computing service and receiving the results of that computing service. While cloud-based services may comprise any type of computer processing or storage, three common categories of cloud-based services **90** are microservices **91**, cloud computing services **92**, and distributed computing services **93**.

(94) Microservices **91** are collections of small, loosely coupled, and independently deployable computing services. Each microservice represents a specific computing functionality and runs as a separate process or container. Microservices promote the decomposition of complex applications into smaller, manageable services that can be developed, deployed, and scaled independently. These services communicate with each other through well-defined application programming interfaces (APIs), typically using lightweight protocols like HTTP, gRPC, or message queues such as Kafka. Microservices **91** can be combined to perform more complex processing tasks.

(95) Cloud computing services **92** are delivery of computing resources and services over the Internet **75** from a remote location. Cloud computing services **92** provide additional computer hardware and storage on as-needed or subscription basis. Cloud computing services **92** can provide large amounts of scalable data storage, access to sophisticated software and powerful server-based processing, or entire computing infrastructures and platforms. For example, cloud computing services can provide virtualized computing resources such as virtual machines, storage, and networks, platforms for developing, running, and managing applications without the complexity of

infrastructure management, and complete software applications over the Internet on a subscription basis.

(96) Distributed computing services **93** provide large-scale processing using multiple interconnected computers or nodes to solve computational problems or perform tasks collectively. In distributed computing, the processing and storage capabilities of multiple machines are leveraged to work together as a unified system. Distributed computing services are designed to address problems that cannot be efficiently solved by a single computer or that require large-scale computational power. These services enable parallel processing, fault tolerance, and scalability by distributing tasks across multiple nodes.

(97) Although described above as a physical device, computing device **10** can be a virtual computing device, in which case the functionality of the physical components herein described, such as processors **20**, system memory **30**, network interfaces **40**, and other like components can be provided by computer-executable instructions. Such computer-executable instructions can execute on a single physical computing device, or can be distributed across multiple physical computing devices, including being distributed across multiple physical computing devices in a dynamic manner such that the specific, physical computing devices hosting such computer-executable instructions can dynamically change over time depending upon need and availability. In the situation where computing device **10** is a virtualized device, the underlying physical computing devices hosting such a virtualized computing device can, themselves, comprise physical components analogous to those described above, and operating in a like manner. Furthermore, virtual computing devices can be utilized in multiple layers with one virtual computing device executing within the construct of another virtual computing device. Thus, computing device **10** may be either a physical computing device or a virtualized computing device within which computer-executable instructions can be executed in a manner consistent with their execution by a physical computing device. Similarly, terms referring to physical components of the computing device, as utilized herein, mean either those physical components or virtualizations thereof performing the same or equivalent functions.

(98) As can now be appreciated, disclosed embodiments enhance low-light images, allowing details that are difficult to see in the original image to become more visible. Enhancement of low-light images can be particularly useful for surveillance, security, and forensic applications, where identifying objects, people, or text in low-light conditions is important. In images containing text, such as documents or signs, enhancing the image can make the text more readable. This can be helpful in scenarios where capturing clear text is crucial, such as reading license plates or identifying street signs in low-light conditions. In photography and video recording, enhancing low-light images can improve the overall aesthetics of the image or video by making details and colors more vibrant and clearer. With the feature of enhancing low-light images, disclosed embodiments can have a wide range of applications across various industries, improving visibility, readability, and image quality in challenging lighting conditions.

(99) The skilled person will be aware of a range of possible modifications of the various aspects described above. Accordingly, the present invention is defined by the claims and their equivalents.

## Claims

1. A system for image enhancement, comprising: a computing device comprising at least a memory and a processor; a denoising preprocessing module comprising a first plurality of programming instructions that, when operating on the processor, cause the computing device to: create a plurality of subsampled subimages from a raw input image; analyze the raw input image to determine image characteristics; determine preprocessing parameters based on the image characteristics; perform an adaptive wavelet decomposition process on each subimage from the plurality of subimages using the determined preprocessing parameters to generate a plurality of frequency domain subimages;

input each frequency domain subimage from the plurality of frequency domain subimages into a corresponding neural network; provide an output of each corresponding neural network to an inverse wavelet module; and provide an output of the inverse wavelet module to an image signal processing pipeline.

2. The system of claim 1, wherein the denoising preprocessing module further comprises programming instructions operable on the processor to create the plurality of subsampled subimages from a Bayer raw input image.

3. The system of claim 1, wherein the denoising preprocessing module further comprises programming instructions operable on the processor to select and utilize one of multiple wavelet types as a decomposition filter in the adaptive wavelet decomposition process based on the determined preprocessing parameters.

4. The system of claim 1, wherein the denoising preprocessing module further comprises programming instructions operable on the processor to create a variable number of frequency domain subimages for the plurality of frequency domain subimages based on the determined preprocessing parameters.

5. The system of claim 1, wherein the denoising preprocessing module further comprises programming instructions operable on the processor to perform adaptive downsampling as part of the adaptive wavelet decomposition process based on the determined preprocessing parameters.

6. The system of claim 5, wherein the denoising preprocessing module further comprises programming instructions operable on the processor to perform processing rows of image data, followed by processing columns of image data.

7. The system of claim 1, further comprising a neural network module comprising a second plurality of programming instructions operable on the processor to implement the plurality of neural networks, wherein each neural network includes a Leaky ReLU activation function.

8. The system of claim 7, wherein the neural network module further comprises programming instructions operable on the processor to implement a plurality of neural network blocks, wherein the plurality of neural network blocks includes at least one convolutional block, and at least one residual block, and at least one Squeeze-and-Excitation block.

9. A method for image enhancement, comprising steps of: creating a plurality of subsampled subimages from a raw input image; analyzing the raw input image to determine image characteristics; determining preprocessing parameters based on the image characteristics; performing an adaptive wavelet decomposition process on each subimage from the plurality of subimages using the determined preprocessing parameters to generate a plurality of frequency domain subimages; inputting each frequency domain subimage from the plurality of frequency domain subimages into a corresponding neural network; providing an output of each corresponding neural network to an inverse wavelet module; and providing an output of the inverse wavelet module to an image signal processing pipeline.

10. The method of claim 9, wherein creating the plurality of subsampled subimages from the raw input image comprises inputting a raw image in a Bayer raw image format.

11. The method of claim 9, further comprising selecting and using one of the multiple wavelet types as a decomposition filter in the adaptive wavelet decomposition process based on the determined preprocessing parameters.

12. The method of claim 9, further comprising creating a variable number of frequency domain subimages for the plurality of frequency domain subimages based on the determined preprocessing parameters.

13. The method of claim 9, wherein the wavelet decomposition process further comprises downsampling.

14. The method of claim 13, further comprising processing rows of image data, followed by processing columns of image data.

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