Analysis of Atmospheric Scattering from Digital Images using Temporal Polarized Vision

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Abstract—Scattering, along with absorption, causes attenuation problems with radar and other measuring devices. Suspended atmospheric particles (particulate matter) are a form of air pollution that visually degrades urban scenery and is hazardous to human health and the environment. Current environmental monitoring devices are limited in their capability of measuring average particulate matter (PM) over large areas. Quantifying the visual effects of haze in digital images of urban scenery and correlating these effects to PM levels is a vital step in more practically monitoring our environment. Current image haze extraction algorithms remove all the haze from the scene and hence produce unnatural scenes for the sole purpose of enhancing vision. We present two algorithms which bridge the gap between image haze extraction and environmental monitoring. We provide a means of measuring atmospheric scattering from images of urban scenery by incorporating temporal knowledge.

In doing so, we also present a method of recovering an accurate depth map of the scene and recovering the scene without the visual effects of haze. We compare our algorithm to three known haze removal methods from the perspective of measuring atmospheric scattering, measuring depth and dehazing. The algorithms are composed of an optimization over a model of haze formation in images and an optimization using the constraint of constant depth over a sequence of images taken over time. These algorithms not only measure atmospheric scattering, but also recover a more accurate depth map and dehazed image. The measurements of atmospheric scattering this research produces, can be directly correlated to PM levels and therefore pave the way to monitoring the health of the environment by visual means. Accurate atmospheric sensing from digital images is a challenging and under-researched problem. This work provides an important step towards a more practical and accurate visual mean sof measuring PM from digital images..

Keywords — RCC, Dehazing, CDC, Digital Images, Temporal Polarized Vision.

I. INTRODUCTION

How air pollution affects the visual appearance of scenes has been a research challenge for scientists. Changes in emissions, urban growth, and many other factors influence the amount and type of pollution suspended in the atmosphere. Suspended particles in the atmosphere are known as particulate matter (PM). PM visually degrades urban scenery and is hazardous to human health and the environment. Current measuring devices calculate the concentration of PM in the local vicinity of the device. These approaches do not measure the overall global concentration of PM over large urban areas and therefore lack accuracy in their measurements. Multiple measurements over a wide area are required to calculate the average PM level. Other means of measuring PM use laser devices and analyze satellite imagery. These methods are expensive, require skilled professionals to operate and are not suited to urban populated areas. Understanding and quantifying the visual effects of the atmosphere over large urban areas captured in digital images is a vital step in measuring global levels of PM more practically and accurately.

Understanding air pollution lies in the challenging process of measuring atmospheric scattering. Atmospheric scattering fluctuates proportionally to the levels of PM in the atmosphere and therefore offer a means of measuring PM. The challenge of measuring atmospheric scattering visually lies in finding the relationship between image pixel values and the atmospheric scattering taking place in the urban scene. The difficulty of finding this relationship lies in accounting for all the many factors that affect the pixel values. There are multiple factors which include: background molecular scattering of light, the position of the sun, the calibration of the camera's radiometric response curve, camera viewpoint, multiple-scattering, presence of non-spherical particles and the background scene reflectance which varies according to illumination.

Currently, haze extraction algorithms exist which remove the haze in a scene. This is ideal from the perspective of enhancing vision but finding the relationship between the extracted haze and overall global PM levels from ground-based images is an under researched problem. We compare existing dehazing algorithms in the context of monitoring atmospheric scattering and present a method of more accurately measuring atmospheric scattering from a sequence of images captured over time. This provides an important step in estimating PM much more practically using imaging devices. The most hazardous subcategory of PM is known as PM10 and consists of particles with diameters less than 10 micrometers. These particles make up most of the haze in urban scenery and greatly affect the visual perception of the scene. This research presents an approach to measure atmospheric scattering from image pixel values using simple off the shelf equipment consisting of a Single-Lens-Reflex (SLR) camera, polarizer filter and color filters.

II. BACKGROUND

In this chapter we describe the theoretical foundation of the proposed research. We start off by defining particulate matter (PM), air light (haze) and current methods of measuring PM. Then we will describe the theory that this research is based upon, which is the physical interaction of light and the atmosphere. The physical models of how light changes and interacts with airborne molecules and particles is studied in order to understand the resultant irradiance captured by images of distant scenes. Light undergoes changes as it passes through the atmosphere. Its wave patterns, intensity and direction changes as the photons come into contact with molecules and aerosols in the atmosphere. We describe a phenomenon known as polarization which happens to light waves as they are scattered by molecules and particles. Then we will explain photographic methods of dealing with this phenomenon known as light polarization. We will then look at the physics of light scattering.

- ***Particulate Matter (PM)***

According to the US Environmental Protection Agency (EPA) [6],

"Particulate matter, also known as particle pollution or PM, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems"

"EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects"

The EPA classifies particles which make up PM into two categories:

Inhalable coarse particles – found close to roads and dusty industries. These particles are larger than 2.5 micro meters and smaller than 10 micro meters in diameter.

Fine particles - found in smoke and haze and are 2.5 micrometers in diameter and smaller. These particles can be directly emitted from sources such as forest fires, or they can form when gases emitted from power plants, industries and automobiles reacting the air.

PM is not only hazardous to human health, but also affects visibility. Particulate matter is the main cause of atmospheric visibility reduction due to haze [7]. Haze is seen as a bluish or brownish obscuration in distant scenes.

A. Methods of Measuring PM

In this section we describe the current methods of measuring PM10 concentrations. According to NASTRO [9], which is a public and private partnership dedicated to improving the management of air quality in North America, the measurements of PM10 are mainly done using the following methods:

a. Gravimetric Methods – exchangeable filters(FRM)
b. Beta Attenuator Methods(FEM)
c. Tapered Element Oscillating Microbalance(TEOM)

Gravimetric Methods - exchangeable filters (FRM) methods use an air pump to draw in ambient air at a constant rate into a specifically shaped inlet where particulate matter is separated by size. Particulate matter is then collected on a filter. The filters are weighted before and after, to determine the net mass increase due to the collected matter. This net mass of particulate matter is measured relative to the volume of air intake which produces a measurement of micrograms per cubic meter of particle matter.

Beta Attenuator Methods (FEM) Beta particles are electrons with a certain energy range. These particles are attenuated according to an approximate exponential function when they pass through particulate deposits on a filter tape. Automated samplers use a filter tape. The unexposed tape is subjected to beta particles and the attenuation is measured and compared to the same measurement done on the same tape but after exposing it to ambient air flow. The particulate matter from the air deposits on the tape and causes a difference in the attenuations measurements. This difference is used to calculate the mass of particulate matter per volume of air.

Tapered Element Oscillating Microbalance (TEOM) consist of a tapered glass element with a filter attached which draws in air. The element oscillates according to a characteristic frequency that decreases as mass accumulate on the filter. This measurement of frequency is used to calculate the accumulated mass of particulate matter which then gives a measure of the PM concentration.

There are many other methods of measuring PM concentrations under research and development and not standard methods used. Some other methods are filter-based. Some apply light or lasers to samples of ambient air and calculating the PM concentration using the scattering and absorption of light [10 & 11]. LIDAR (Light Detection and Ranging) is an optical remote sensing technology that can be used to measure PM concentrations [11]. There is also a method of measuring, which measures the shock waves (acoustic energy) caused by the impact of particles with a probe inserted into the air flow [10].

- ***Air light (Haze)***

Air light or haze is the brownish or bluish color we see when we look at distant objects. This visible effect is due to the scattering of light by the atmosphere towards the viewer. The atmosphere consists of a mixture of molecules and particles of various sizes. The following figure illustrates what happens when we take a picture of distant objects through the atmosphere during the daytime.

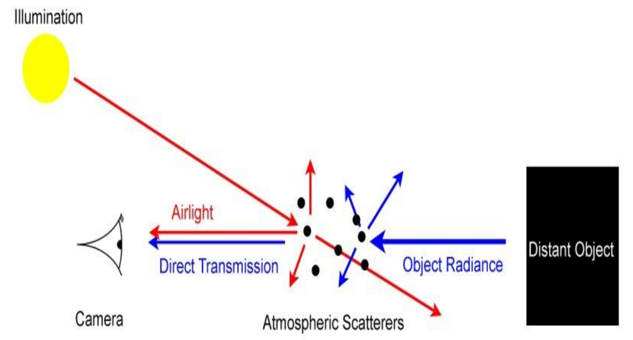

Figure 1: This diagram shows what happens when we view a distant object through the atmosphere.

The main illumination on a clear sunny day is the sun. The illumination from the sun is scattered by molecules and particles in the atmosphere in all different directions. Some of this scattered light is scattered towards the viewer (camera) which results in an additive radiance that increases the brightness of distant objects. This is known as air light. The further away an object is, the brighter it appears. This is because the more atmospheric medium there is between a viewer and an object; the more scattering of light towards the viewer takes place. The object radiance is also attenuated due to scattering and absorption as it travels towards the viewer. The object radiance is partially scattered out of the line of sight and absorbed by the particles in the atmosphere. The direct transmission is the light radiance that remains after the object radiance is attenuated along the path towards the camera.

- ***Light Polarization***

Polarization is a property of transverse waves. It describes the orientation of vibration of the wave in the cross sectional plane perpendicular to the direction of motion. Light is a transverse electromagnetic wave. A light wave travelling forward can oscillate up and down, side to side or in any intermediate direction. Normally a light wave is composed of a collection of waves vibrating in all directions perpendicular to its line of propagation. If the light waves vibrate consistently in a particular orientation as it moves forward, the light is said to be polarized.

Natural light emitted from the sun is un polarized. This means that the electromagnetic waves are oscillating in random directions about the axis of motion. When unpolarized light is reflected the resultant light is always polarized to a certain extent. Light can also be polarized by both double refraction and scattering in gases. The latter form of light polarization is of concern in this research and will be looked at in-depth.

As light rays pass through a medium it is scattered by the molecules and any suspended particles in that medium. The scattered light is partially polarized. A polarizer filter as we will discuss next can be used to control the capture of this scattered polarized light when taking pictures.

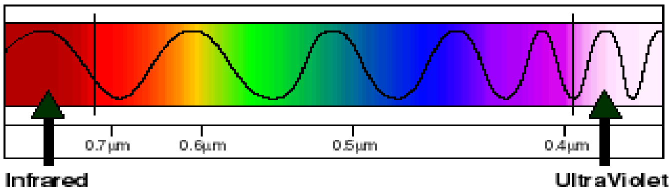

Figure 2: The visible electromagnetic radiation spectrum [21]

Light scattering is selective. This means that different sizes of particles scatter different wavelengths of light more than others. This can be explained by Rayleigh scattering and seen every day in nature as we observe the colors of the sun and sky. The atmosphere is mostly composed of molecules (small particles) and Rayleigh scattering is inversely proportional to the fourth power of the wavelength. This means that the shorter wavelengths of blue light will scatter more than the longer wavelengths of green and red light. This explains why the upper atmosphere of earth scatters more blue light down to us which makes the sky appear blue during the day. This is also why the setting sun appears orange or reddish. This is because the sun's rays are passing through much more atmosphere compared to when the sun is overhead. The increase in atmosphere means an increase in scattering out of the direction of the illumination. Since more blue and green light than red light is scattered away, the sun appears reddish.

1) Rayleigh Scattering

Rayleigh scattering theory was derived by Lord Rayleigh in 1871. This law models the scattering of light by particles much smaller than the wavelength of light. This primarily occurs as light radiation travels through gases and is scattered by the molecules of that gas. The blue color of the sky has been explained and proved by the Rayleigh scattering law. The molecules present in the upper atmosphere of the earth are wavelength selective and scatter more blue light than the rest of the colors in the visible spectrum. Due to this, more blue light is scattered towards us which makes the sky appear blue. Rayleigh scattering also makes the setting sun appear reddish. This is because more blue and green light is scattered out of the line of sight as you look at the sun resulting in an orange or reddish appearance of the sun.

2) Mie Scattering

Mie's theory, also known as Lorenz-Mie theory and Lorenz-Mie-Debye theory, is the generalization of Rayleigh theory and encompasses spherical particles similar or slightly larger in size than the wavelength of light. The diameter of particles is comparable to the wavelength of light(between0.03and32timesthe wavelength of visible light (0.38 to 0.75 micrometers)). Particles that satisfy this condition are known to be within the Mie regime and tend to scatter more light in the forward direction than in the backward direction and less light in the sideway directions. Mie scattering is valid for all possible ratios of diameter to wavelength, unlike Rayleigh scattering which is valid only for diameters that are much smaller than the wavelength[35].Mie scattering, unlike Rayleigh scattering, is not strongly wavelength dependent.

III. METHODOLOGY

The first step in this research was a procedure known as radiometric camera calibration. This is done to linearize the captured images according to the light response curve of the imaging device. We also describe the image processing techniques that we incorporated in this thesis to be able to extract the knowledge efficiently from the images. We will then reconstruct the research undertaken in the image dehazing algorithms (sections 4.3-4.5) After achieving we describe our models of atmospheric scattering measurement and depth estimation.

- ***Radiometric Camera Calibration***

Radiometric camera calibration is a standard pre-processing step in computer vision. An image of a scene is a two-dimensional array of brightness values. Each pixel of an image consists of red, green and blue color components whose values range from 0-255 for 8-bit precision. The brightness values of each pixel are not a measure of the actual physical light radiance emitting from the scene being photographed. There is a nonlinear mapping unique to each image-capturing device that dictates the relationship between scene radiance and pixel values. Digital cameras introduce nonlinearities in order to mimic the response characteristics of film and to compose the high dynamic range of light prior to quantization. For this reason the relation between the actual physical light radiance coming from a scene is nonlinearly related to the brightness of the corresponding image pixel.

The graph that maps the pixel brightness values to the physical measure of light irradiance is known as the radiometric response curve. The following subsection describes the approach we took to calibrate our camera. We calibrated a Panasonic Lumix DMC-FZ8 and a Canon 20D DSLR camera. The latter camera is a semi-professional Single Lens Reflex (SLR) camera and will allow us to obtain more accurate results due to its larger imaging sensor with deeper bit-depth per pixel.

Obtaining the Response Curve

In order to calibrate the radiometric response of a camera we used the method of Debevec and Malik [4]. The following steps outline the process of obtaining the response curve :

1. Set the camera to full manual mode. Adjust the camera so that it is fixed in place and does not move.
2. Take pictures at equal increments or decrements of exposure. Shutter speed variation is the recommended approach over aperture change.

Ideally the more pictures taken, the more accurate the response curves. Around five pictures are needed to produce a decent curve. Make sure the pictures are being captured in RAW format to prevent any extra nonlinear interference from the camera's image processing pipeline. Raw format

Convert the RAW images to TIF uncompressed format to be able to process them in Matlab. TIF uncompressed format is compatible with Matlab and retains the per pixel information that we need in order to undertake our experiments. We used uncompressed TIFF images with 48 bits per pixel (16 bits for each color).

The response curve looks like the following:-

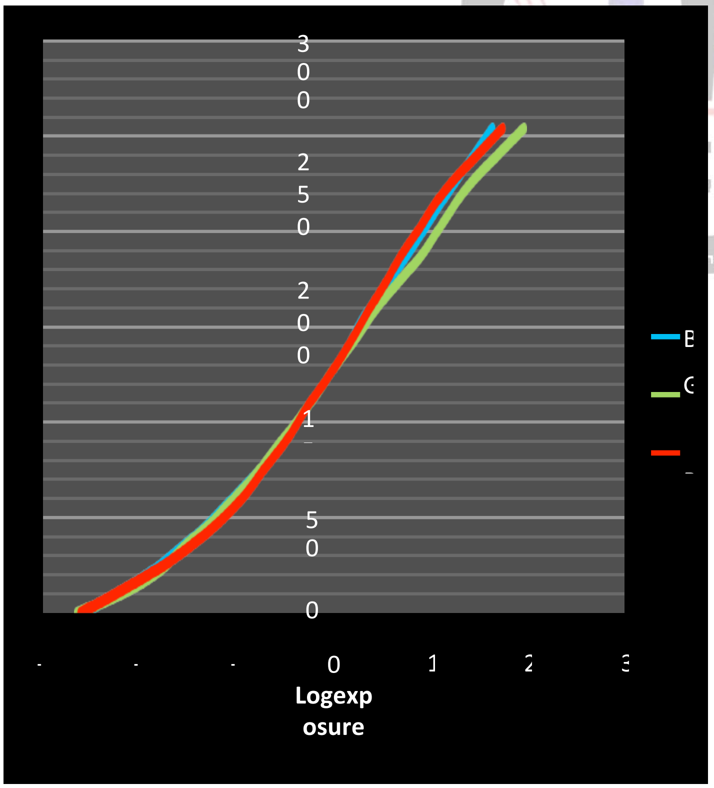

Figure 4: Radiometric response curve measured for the Canon 20D DSLR

images will hold the unprocessed data we need in order to get accurate measurements of light radiance. We took a sequence of images at varied shutter speed as shown below. Scenes with high ranges of light and dark regions produced smoother curves. Ideally a Macbeth chart should be used to calibrate the camera. The Macbeth chart is an industry standard used for calibration. It consists of a board with 24 color patches arranged on it. These color patches have known reflectance that enables it to be used for calibration. We did obtain a Macbeth chart to be able to perform this procedure but before we obtained this chart we approximated the procedure by printing our own Macbeth chart with the approximated equivalent color patches. We did this by printing out the approximate RGB colors of the Macbeth chart.

A. *Image Registration*

In computer vision, sets of data acquired by sampling the same scene at different times, or from different perspectives, will be in different coordinate systems. Image registration is the process of transforming the different sets of data into one coordinate system. Registration is necessary in order to be able to compare or integrate the data obtained from different measurements [41].

This research is based on capturing images of scenery over time and comparing them based on the assumption that the depth of the scene objects is constant. The scene is kept constant to measure the other variations in radiance due to haze. Even though the camera is positioned at the same location and orientation before capturing every image there is still a minute error as the camera is repositioned manually. This causes the discrepancy in coordinate system between the images. This is a problem and requires image registration to align all the images together into one single coordinate system. follows.

- ***Polarization-based Image Dehazing***

In order to extract the air light (refer to background section 2.3) we follow two approaches. The first is the approach undertaken by the paper: "Polarization-based Vision through Haze" [1]. We used the dehazing algorithm described in this paper to separate out the air light in the scene. The second approach is the dichromatic framework which also separates out the air light but depends on images taken under different atmospheric conditions (e.g. dense haze, mild haze, clear day).

- ***Dehazing Algorithm***

Two images are taken of a scene of an urban horizon with haze limiting visibility. The two images taken are captured with different orientations of a polarizer filter. In our case we took the pictures from an elevated area in the center of Cairo. The sun was situated approximately perpendicular (90 degrees) to the viewing direction. One of the images was taken with the linear polarizer filter positioned parallel to the viewing direction in order to limit the polarized light reflecting off the air particles in our scene. The other image was taken with the polarizer filter positioned normal to the viewing direction to allow the partially polarized air light to pass through the lens. The air light is the dominating polarized light detected by the camera. Scattered light is always partially or fully polarized perpendicular to the plane of incidence. In our case the plane of incidence is defined by the plane between the illumination source (sun), the scattering particle and the camera. As the sun is roughly perpendicular to our viewing direction, the air light is polarized in the vertical axis (i.e. the waves are oscillating up and down). When we rotate the polarizer filter to be perpendicular to the plane of incidence (in this case vertically), the polarized air light is allowed through the lens. When we rotate the polarizer filter parallel to the plane of incidence (in this case horizontally),the polarized air light is filtered out of the lens.

The total irradiance captured by the camera is the sum of the direct transmission and air light (refer to background section 2.3 for a description of this). The equation for the total irradiance is:

$$I = D + A$$

where is I the total irradiance, D is the direct transmission and A is the air light. These are all per pixel quantities. We assume that the light reaching the camera is dominated by the polarized air light and therefore the direct transmission is minimally polarized [1]. Therefore the variation due to the polarizer rotation is from the air light in the scene.

The Dehazing Algorithm:

This algorithm refers to the work described in section3.3.Two images are taken at approximately parallel and perpendicular orientations of the polarizer filter provide us with two maps of scene point irradiance values. We will call the image taken with the parallel polarizer, the best polarization image and the perpendicular polarizer, the worst polarization image.

We denote the best polarization irradiance by $I_\perp$ and the worst polarization irradiance $I_{||}$. The total irradiance $I_{total}$of best and worst polarization statesis:

$$I_{total} = I_\perp + I_{||}$$

IV. Measuring Atmospheric Scattering and Unscaled Depthm

The transmittance of a medium is a measure of how much the medium transfers light through it. A fully opaquemediumhasatransmittanceequalto0andafullytransparentmediumhasatransmittanceof1.In order to recover the transmittance of a scene and measure the atmospheric scattering coefficient, denoted by βwe implemented two optimization algorithms.

The first optimization is a stand alone optimization asitis not based on any previous dehazing algorithm. We refer to it as the Color Optimization. It takes a sequence of images captured over time and solves for the set of transmittances and scene radiance pixels that best fit the model of haze formation in images. We will refer to this model of haze formation as the haze image formation model. This model is used in the dehazing algorithms and can be seen in equation 3.3.4. We will reintroduce it in the following section. The second optimization algorithm is an extension of the dehazing algorithms. We will refer to this optimization as the *Constant Depth Constraint* (CDC). This optimization decomposes the scaled depth maps produced by each of the three dehazing algorithms (polarization-based, temporal and dark channel) into a single depth map and set of scattering coefficients that best fits the sequence of images according to a transmittance constraint. Both these optimizations are performed using nonlinear optimization. We will describe them in the following sections.

- ***Color Optimization***

As part of the goal of this thesis to analyze the atmospheric scattering from digital images in order to more accurately measure particulate matter, we designed and implemented the Color Optimization algorithm. This algorithm is based on a simple ratio derived from the haze image formation model which accounts for the addition of air light radiance as distances increase and attenuation of scene radiance due to scattering. This model is described by the following equation. We use a sequence of multiple images of the same scene captured over time and this model to find two unknowns: the scene radiance $R$and the scaled depth βz. In other words we are trying to optimize to find the scene radiance and scaled depth of the scene that best fit the haze image formation model applied to a sequence of images of the same scene captured over time. This is an optimization problem that applies this model in a temporal fashion to find the two unknowns.

$$I = Re^{-\beta z} + A_{\infty}(1 - e^{-\beta z}) \quad 4.1.1$$

where I is the image irradiance per pixel, R is the scene radiance, β is the scattering coefficient of the atmosphere and z is the depth of the scene object relative to the camera. A_{∞} is the atmospheric air light at infinite distance which we can obtain from the sky region similar to the method the polarization-based dehazing uses. We rewrite the above equation by simply replacing and simplifying the variables into a form more intuitive to our optimization:

$$I_i^c(x) = R^c(x)T_i(x) + A^c(1 - T_i(x))$$

The superscript signifies the value is over the three color channels of red, green and blue. The subscript signifies that this variable i varies with time. $T_i(x)$ is the global transmittance of each image captured at time i. This defines the transmittance at time for each patch of the scene represented over , where x is the spatial index over the pixels. $T_i(x)$ is defined by the transmittance equation:

$$T_i(x) = e^{-\beta z}$$

The scene radiance(over the R three color channels) in equation 5.1.1.2 varies over time as the illumination position changes (e.g. the sun moving with time). This is according to Lambert's law of diffuse reflection [34]. We assume that the scene radiance does not vary much over the limited period of time that our sequence of images is captured over.

We reshuffle the variables of the equation into the following:

$$I_i^c(x) - A^c = (R^c(x) - A^c)T_i(x)$$

We use least squares regression to optimize the above constraining equation over a sequence of images capturedovertime.Thisformsthefollowingerrorfunctionthatrepresentsthesquareddifferencebetween both sides of equation 5.1.1.3 over all color channels, pixels and time. We minimize this error function in order to find the best-fit values for the transmittance for each patch of the input images at each time and one 2-dimensional matrix of scene radiance $R^c(x)$:

$$\varepsilon = \sum_i \sum_x \sum_c [I_i^c(x) - A^c - (R^c(x) - A^c)T_i(x)]^2$$

.

We minimized the above error function over each 10x10 pixel patch of a sequence of digital images of the same scene captured over time. We tried multiple approaches of solving this minimization problem. First we used a gradient descent search for the minimum solution. We tried to enhance the minimization by performing a constrained search that constrained the transmittances and radiance between 0 and 1. After still being very slow to converge we enhanced the optimization by providing the partial derivatives equations instead of relying on MATLAB's internal ways of computing them automatically. MATLAB's automatic partial derivative computer was slow in our case as we were dealing with large matrices of color pixels. The partial derivatives areas follows:

$$\frac{\partial \varepsilon}{\partial T_i(x)} = \sum_x \sum_c [I_i^c(x) - R^c(x)T_i(x) - (1 - T_i(x))A^c](A^c - R^c(x))$$

VI.

$$\frac{\partial \varepsilon}{\partial R^c(x)} = \sum_i \sum_c [I_i^c(x) - R^c(x)T_i(x) - (1 - T_i(x))A^c](-T_i(x))$$

VII.

Thesepartialderivativesarethegradientsoftheerrorfunctionand equal0attheminimumsolution.After still taking a long time to converge we decided to use our own iterative method.

We solved both partial derivative equations analytically for the minimum solution for $R^c(x)$ and $T_i(x)$
Where these partial derivatives reach zero. The atmospheric air light intensity in each color channel and the image irradiance at specific times and color channels and space over the image are all known variables. The two partial derivative equations shown above each have one unknown: $R^c(x)$ in the first partial derivative and $T_i(x)$ in the second equation. We reshuffle around the variables and summations in each of these partial derivative equations so that each computes $R^c(x)$ and $T_i(x)$ directly. We then iterate back and forth between solving for $R^c(x)$ and then solving for $T_i(x)$.
The equations for $R^c(x)$ and $T_i(x)$ after reshuffling equations are:

$$T_i(x) = \frac{-\sum_x \sum_c (I_i^c(x) - A^c)(A^c - R^c(x))}{\sum_x \sum_c (A^c - R^c(x))^2}$$

VIII

$$R^c(x) = \frac{\sum_i T_i(x)(I_i^c(x) - A^c + A^c T_i(x))}{\sum_i (T_i(x))^2}$$

IX

There are many variables in this non-linear system of two equations shown above. The

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transmittance is defined over time and space (over each image taken at time), the image irradiance is defined over space, time and color channel, the atmospheric air light is defined over the color channels and the scene radiance is defined over space and the color channels. Due to the large number of unknown variables there comes a high possibility of multiple local minima solutions to this problem. In order to try and remedy this we clamped the maximum transmittance to the value of one so that we ensured that exactly one solution scaled to an unknown scalar was returned. When comparing the estimated transmittances to the real transmittances, we also applied this scaling by dividing by the largest value so that the largest transmittance in the set had a value of one. By this, we ensured that both transmittance sets were scaled by the same amount and could be compared. The atmospheric air light A^c in equations 5.1.1.7 and 5.1.1.8 is set to the largest irradiance value found in the image (i.e. the intensity of the brightest pixel in the sequence of digital images). This is to ensure that one minimum solution is found and scaled by the value of the atmospheric air light. Unfortunately this does not guarantee that no other local minima will be found.

- **Constant Depth Constraint (CDC)**

This second optimization algorithm is a simple optimization based on the relation between the transmittance, atmospheric scattering and depth (described in equation 5.1.2 below). This optimization method extends the already existing dehazing algorithms (polarization-based, temporal and dark channel) and the color optimization described above.

This optimization is based on the simple model of transmittance described by the following equation:

$$T = e^{-\beta z}$$

X

where T is the transmittance, β is the atmospheric scattering coefficient and z is the depth.

Given the transmission map produced by any one of the dehazing algorithms or the color optimization, We can solve for asset of scattering coefficients and a single depth map that best fit equation5.1.2.1.

We implement the standard linear sum of squares regression to find the best fit variables to the transmittance model. Subtracting one side of equation 5.1.2.1 from the other yields the following error function to minimize:

$$\varepsilon = \sum_i \sum_x [\beta_i z(x) - \log(T_i(x))]^2$$

XI.

We attempted to minimize the error function above using the same steps of the color optimization. These steps included fist trying the built in functions of MATLAB. These are *fminunc* for unconstrained minimization and *fmincon* for constrained minimization. When using both these equations, the converging was extremely slow and therefore needed to be speedup. It was extremely slow even on small patches of dimensions 10x10. We followed the successful approach of the color optimization in speeding up the convergence. We calculated the partial derivatives of equation 5.1.2.2 by hand. These are:

$$\frac{\partial \varepsilon}{\partial \beta_i} = \sum_x [\beta_i z(x) - \log(T_i(x))] z(x)$$

XII.

$$\frac{\partial \varepsilon}{\partial z(x)} = \sum_i [\beta_i z(x) - \log(T_i(x))] \beta_i$$

XIII

Again, we solved for these partial derivatives (gradients) assigned to zero. We reshuffled these equations so that the two unknowns could be calculated directly. These equations become:

$$\beta_i = \frac{\sum_x T_i(x) z(x)}{\sum_x (\beta_i)^2}$$

XIV

$$z(x) = \frac{\sum_i T_i(x) \beta_i}{\sum_i (\beta_i)^2}$$

Using the above equations we are able to iteratively solve for the scattering coefficients and then solve for the depth map and then loop again. We clamped the maximum scattering coefficient to a value of 1 to ensure that only one possible solution would be found. We compared the estimated set of scattering coefficients with the real set but again scaled so that the maximum of the set is 1. This allowed us to properly compare the estimated and the real values.

V. CONCLUSION

From the results described in the previous sections, we know that Scattering is the process by which "small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions. we can see experimentally through the use of simulations and real live images two direct the contributions of this thesis: Color Optimization and Constant Depth Constraint (CDC). These two algorithms have provided valuable steps in the analyzing haze-filled scenes using simply the temporal factor of a sequence of images captured over time. The color optimization method does not rely on any of the limiting parameters of the previous dehazing methods to dehaze the scene and produce an accurate transmission map. The CDC optimization method quantifies the atmospheric scattering in a sequence of images of a certain scene captured over time. The goal of this is to pave the way to measuring particulate matter from digital images. We achieve this by measuring the atmospheric scattering coefficient which is strongly correlated to the levels of particulate matter (PM). In addition to this we recover an enhanced depth map of the scene. This depth map has been compared to the known dehazing algorithms and found to be more accurate than existing dehazing methods. When dealing with vast urban scenes a small increase in accuracy provides a large decrease in the margin of error of estimating the distances in the scene.

The polarization algorithm is one of the simplest methods of dehazing. It is an instant approach that allows the images to be taken at a point of time and the analysis done at the same time. Despite this it has a weakness in estimating atmospheric scattering. This is the instability it

displays with errors in the degree of polarization. It also suffers from manual settings of the polarizer filter which needs to be automated in order to be practically usable. The dark channel and dichromatic dehazing methods show instability in other areas of the experiments, such as, image noise and errors in atmospheric air light estimates. The dark channel shows some unstable results due to its prior which produces errors in the results and therefore prevents an accurate measurement of atmospheric scattering. The dichromatic method uses temporal knowledge but relies on too many external conditions, such as, changes in haze and overcast skies (as it does not handle changes in spectral illumination).

The color optimization presented in this research displays a promising contribution to measuring atmospheric scattering visually from images captured over time, a more accurate depth map of the scene and dehazing haze-filled scenery. Proven by experimental verification, this thesis forms a promising framework to analyzing urban atmosphere much more accurately and therefore provides a means to measure PM levels visually

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