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ORIGINAL ARTICLE

MTF Measurements for the Imaging System Quality Analysis

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ABSTRACT

A test system based on Modulation Transfer Function (MTF) was developed and a systematic theoretical MTF measurement approach is introduced to measure the quality of imaging systems. The test system is composed of 6 different optics, illumination module, 2 different CCD cameras, a 1951 USAF resolution test target, fine positioning stages and the data processing software developed under MATLAB to calculate the image contrast at various spatial frequencies and to plot the MTF graphs. Results are presented using 8 different light sources for the 4 different lenses and their 6 different combinations: Rodenstock Apo Rodagon D 2x (Retro) with 1.6x extension tube, Sill Optics Correctal TL72/1.5 Telecentric Lens, Navitar Zoom 6000 motorized lens with 0.75x and none lens attachments and 2x-F mount zoom adapter, Navitar 12x Zoom lens with 0.5x and 0.75x lens attachments and 2x-F mount zoom adapter.

Key Words: *MTF, Resolution, Bar Pattern, Contrast Transfer Function, 1951 USAF Resolution Test Target, Image Quality*

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1. INTRODUCTION

The Modulation Transfer Function (MTF) represents the capability of an imaging system to capture the information content of an object as a function of the spatial frequencies, determining image sharpness and resolution. MTF in a digital image decreases as the spatial frequency increases, and with a MTF graph, it is possible to determine the limit of resolution. This limit depends on the characteristics of all the series connected optoelectronic elements. And the system MTF integrates the modulations occurring in all the elements affecting the digital image.[1,2,3,4,5,6] The system MTF is composed of the multiplication of each element's MTF[4,5,6,7] and depends on the wavelength. Methods for measuring the MTF have been studied in literature, associating object image, spatial resolution and sharpness.[2,3,4,5,6] However, imaging systems incorporate different technologies that complicate testing, but it is still considered the MTF one of the best criteria to determine image quality for these complex imaging devices. MTF can reflect the response of the imaging system at different spatial frequencies, thus it is one of the most accurate and direct parameter to evaluate the imaging quality of an imaging system. It has traditionally been measured from a line spread function (LSF)[8] which can be obtained by imaging either a narrow slit or a sharp edge. While the slit response is a direct measure of the LSF convolved with the width of the slit, the edge response or the edge spread function (ESF) is differentiated to obtain the LSF.[9] The MTF can also be measured by imaging a bar-pattern to obtain the square-wave response function (SWRF).[10] In this case, the MTF is directly measured from the image intensity modulations obtained in response to similarly sized and spaced attenuating bars. The bar pattern method does not require a complicated imaging set-up as it is not highly sensitive to central axis alignment, and allows for a simple and quick calculation of the MTF at discrete frequencies. It is sensitive, however, to the measurement of the zero-frequency modulation that is used as a normalization factor. It is usually approximated from relatively large areas of the bar material and air.[11]

There are many ways to measure the MTF of an imaging system, which can be basically divided into two categories. The first one is by using fixed target,[12] of which the measuring result is confined with the sampling area which has accidental chanciness. The second one is by using random signal,[13] which usually has a complete sampling area, but relatively high noise and needs more perplexing arithmetic. The MTF of the imaging systems can be measured directly by using sinusoidal grating pattern, but the design and fabrication of sinusoidal grating pattern has a more complex procedure and a lower accuracy than that of rectangular grating pattern. To measure practical and accurate MTF, rectangular grating patterns are preferable. However by using rectangular grating pattern, the contrast transfer function (CTF) of the CCD camera can be achieved straightly, after using special algorithm the CTF can be converted into MTF.[14]

The purpose of this study is to find the MTF graphs of 6 different optical imaging systems using 8 different light sources. The aim of using 8 different light sources for MTF measurements is to find the effect of different light sources on MTF and find the best light source for all combinations. Using these MTF graphs it can be interpreted the quality of the optical imaging systems. The optical combinations used in this project are designed for small FOV (Field of view) and high resolution monochromatic imaging applications.

2. THEORY

For a digital camera, the image is a matrix of $k \times l$ pixels, where each pixel is an intensity gray level (0 for black and 255 for white) forming the image of the object. The imaging systems is a multielement device with a MTF defined by the lens MTF (MTF_L), the CCD image sensor MTF (MTF_{CCD}), and the electronic processing MTF (MTF_e). Therefore, the system MTF can ben shown in Eq. 1.

$$MTF = MTF_L \times MTF_{CCD} \times MTF_e \qquad (1)$$

Both the lens response (MTF_L) as the CCD sensor (MTF_{CCD}) have been developed theoretically,[3,4,5,6,7] and they behave as a low pass filter with a resolution given by the size of the lens and the width of the CCD pixel, respectively. The MTF_e of the electronic processing depends on the electrical signal conditioning and digital image treatment, which includes image enhancement filters and compression. The MTF, in general, is a plot of the intensity measure in gray level percentage versus spatial frequency (in line pairs per millimeter, lp/mm); resulting in a map of image contrasts for various frequencies. A direct form for measuring the MTF is to use an object with a known spatial frequency (test target) and measuring its image intensity. To calculate image contrast, Eq. 2 is used:

$$M' = contrast = \frac{Imax - Imin}{Imax + Imin} \qquad (2)$$

Where I_{max} is the maximum gray level and I_{min} is the minimum gray level projected on the image plane by the reference object. The MTF is calculated using Eq. 3.

$$MTF(f) = \frac{M'(f)}{M(f)} \qquad (3)$$

Where M is the object modulation for each spatial frequency considered and M' is the modulation of the image.[3,4,5,6,7] M' for each spatial frequency can be calculated using Eq.2. Some methods for measuring the MTF use a test target with calibrated M at several spatial frequencies: bar pattern (binary object) or sine pattern (gray levels object).[1,2,3,4] In this work, the MTF measurements for the imaging system quality analysis is done by a rectangular grating pattern 1951 USAF resolution test target. Resolution tests on imaging systems are still commonly performed using 1951 USAF resolution test target.[15,16,17,18,19,20,21] 1951 USAF resolution test target is a resolution test pattern conforms to MIL-STD-150A standard, set by US Air Force in 1951. It is still widely accepted to test the resolving power of optical imaging systems such as microscopes and cameras, although MIL-STD-150A was cancelled on October 16, 2006.[22] The pattern consists of groups of three bars with dimensions from big to small. The largest bar the imager cannot discern is the limitation of its resolving power.[23] Each group consists of six elements, which are progressively smaller. The elements within a group are numbered from 1 to 6. Odd-numbered groups appear contiguously, 1 through 6, at the upper right corner. The first element of even-numbered groups is at the lower right, with the remaining five elements, 2 through 6, at the left. Each even-odd pair makes up a layer, with the next smaller even-odd pair near the center as seen in Figure. 1.

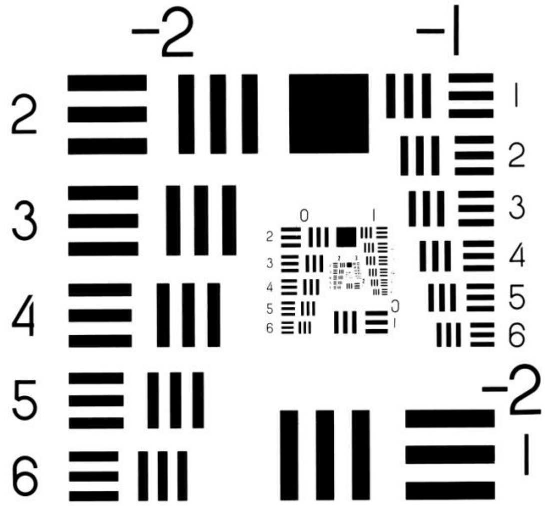

Figure 1. USAF 1951 test target.

The resolution of each groups and elements are determined by the Eq. 4.

$$Resolution\left(\frac{lp}{mm}\right) = 2^{group+\frac{element-1}{6}} \qquad (4)$$

See Table 1.

Table 1. Number of Line Pairs / mm in USAF Resolving Power Test Target 1951.[24]

Number of Line Pairs / mm in 1951 USAF ResolutionTest Target										
Element	**Grup Number**									
	-2	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0
2	0.280	0.561	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144.0
3	0.315	0.630	1.26	2.52	5.04	10.10	20.16	40.3	80.6	161.0
4	0.353	0.707	1.41	2.83	5.66	11.30	22.62	45.3	90.5	181.0
5	0.397	0.793	1.59	3.17	6.35	12.70	25.39	50.8	102.0	203.0
6	0.445	0.891	1.78	3.56	7.13	14.30	28.50	57.0	114.0	228.0

In theory, in each spatial period of the rectangular grating pattern, the transmissivity jumps between 0 and 1, so the contrast of the grating pattern (named M) is close to 1.With the increase of the spatial frequencies, the contrast of the image collected from the imaging system (named M') which is defined as in Eq. 2 will decrease.[14] In Eq. 2, I_{max} and I_{min} can be described by the maximum and minimum light intensity of the image collected from the imaging system. When the spatial frequency of the object is *f*, the MTF of the imaging system at this spatial frequency is defined as the rate of the contrast of the imaging system image to the contrast of the sinusoidal grating pattern.[25] Since what we use is not a sinusoidal grating pattern but a rectangular grating pattern, the rate of the contrast of the imaging system image to the contrast of the rectangular grating pattern is not the MTF but the CTF (Contrast Transfer Function) of the system.

$$CTF(f) = \frac{M'(f)}{M(f)} \qquad (5)$$

MTF is based on sine wave response, but we work with a bar chart. The contrast ratio obtained directly from a bar chart is called the contrast transfer function, Eq. 5. CTF is rarely referred to in the literature. It is not the same as MTF.[26]

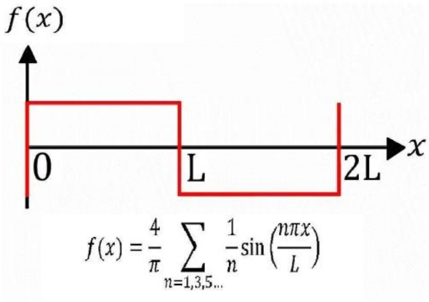

Figure 2. Representation of square wave function.[26]

A portion of a bar chart can be approximated by a periodic function called a square wave, illustrated in Figure.2 for period 2L (frequency = f = 1/2L). Fourier transform mathematics teaches us that any periodic function can be expressed as an infinite sum of sine functions, starting with the fundamental,

$$\sin\left(\frac{\pi x}{L}\right) = \sin(2\pi f) \qquad (6)$$

And including harmonics,

$$\sin\left(\frac{n\pi x}{L}\right) = \sin(2n\pi f) \qquad (7)$$

For n = 2, 3, 4… The equation for the square wave is shown above. It only has odd harmonics (n = 3, 5, 7...). The amplitude of the fundamental frequency of the bar pattern is $\frac{\pi}{4}$ = 1.273 times the amplitude of the bar pattern itself. To obtain MTF from CTF, CTF must be multiplied by a factor of $\frac{\pi}{4}$,[26,27] hence,

$$MTF(f) \cong 0.785 \times CTF(f) \qquad (8)$$

Eq. 8 is only accurate at relatively high frequencies where response is dropping where the harmonics are strongly attenuated. These are the frequencies of interest. The exact equation for relating MTF(f) to CTF(f) was given by Coltman (1954):10

$$MTF(f) = \frac{\pi}{4} \times \left[CTF(f) + \frac{CTF(3f)}{3} - \frac{CTF(5f)}{5} + \frac{CTF(7f)}{7} ....\right] \qquad (9)$$

The signs in this equation beyond n = 7 are quite irregular.

3. EXPERIMENTAL

The test system based on Modulation Transfer Function is setup to measure the imaging system quality. This system is composed of illumination module, six different lens combinations, 4 and 16 Megapixel CCD cameras, USAF 1951 resolution test target, x-y-z fine positioning stages and data processing software. The software is developed under MATLAB for the MTF measurements, calculating image contrasts at spatial frequencies and plotting MTF graphs.

a. Illumination Module

Illumination module is composed of 8 power leds shown in Figure. 2 and 3, like a sphere shape at radius 100 mm distance between the front edge of the light source and the illuminated object. All the eight lights look at the center of the sphere. The test target is put at this center and illuminated homogeneously. Ground glass diffusers are used in front of the power leds to obtain the homogeneous light sources shown in Figureures 4 and 5. 8 light sources are mounted to illumination module at same angle about 20 degree with the optical axis shown in Figure. 2 and 3.

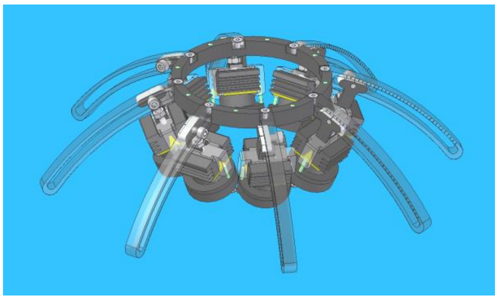

Figure 2. Solid model of illumination module.

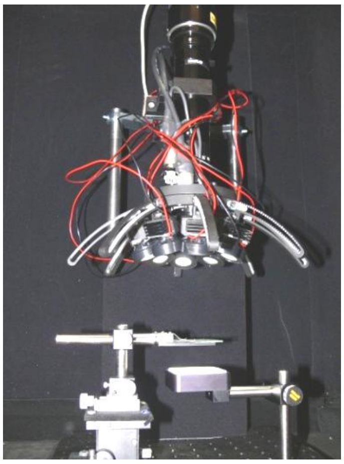

Figure 3. Illumination module at test setup.

Figure 4. Power LED system at test setup.

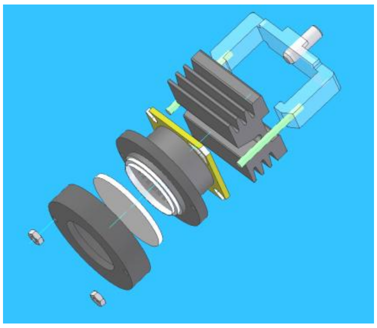

Figure. 5. Solid model of illumination power LED system

b. Lens Combinations

In tests, 4 different lenses and their 6 different combinations are tested. 2 fixed magnification lenses and 2 motorized zoom lenses with two lens attachments are tested. In tests, Rodenstock Apo Rodagon D 2x 75 mm f/4 lens is used in retro position with 1.6x magnification extension tube and modular focus, Sill Optics Precision Telecentric lens which is a specialized lens used in machine vision and Navitar 12x Zoom and Zoom 6000 High magnification high resolution lenses are used. Navitar high magnification zoom lenses have capability of adding in front of the lenses a lens attachment which changes the field of view, magnification and resolution settings of the lens. Navitar high magnification zoom lenses are used in MTF tests with 0.75x, 0.5x and no lens attachment combinations. Lens and camera combinations are listed in Table 2 and shown in Figure. 6, 7, 8 and 9.

Table 2. Lens and camera combinations.

	Lens	Magnification	Image Pixel Resolution	Working distance (mm)	Sensor diameter (mm)	Focuser	Camera Mount
Combination 1	Rodenstock Apo Rodagon D 2x (Retro) with 1.6x extension tube	1.6	3248x3248	110	43.3	Modular	F-mount
Combination 2	Sill Optics Correctal TL72/1.5 Telecentric Lens with F-mount (S5LPJ0066)	1.5	3248x3248	122	43.3	none	F-mount
Combination 3	Navitar Zoom 6000 motorized lens with 0.75x lens attachment and 2x-F mount zoom adapter	1.05x - 6.75x	2048x2048	113	21.5	motorized	F-mount
Combination 4	Navitar Zoom 6000 motorized lens with no lens attachment and 2x-F mount zoom adapter	1.4x – 9x	2866x2866	93	30	motorized	F-mount
Combination 5	Navitar 12x Zoom lens with 0.5x lens attachment and 2x-F mount zoom adapter	0.58x – 7x	1500x1500	165	16	motorized	F-mount
Combination 6	Navitar 12x Zoom lens with 0.75x lens attachment and 2x-F mount zoom adapter	0.87x – 10.5x	2048x2048	108	21.5	motorized	F-mount

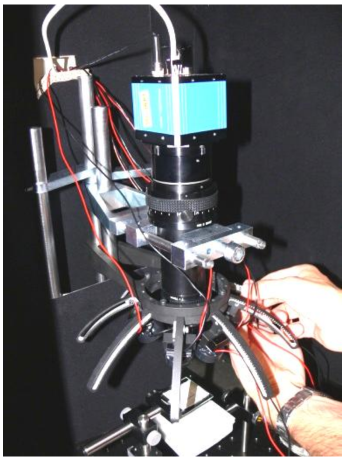

Figure 6. Combination 1.

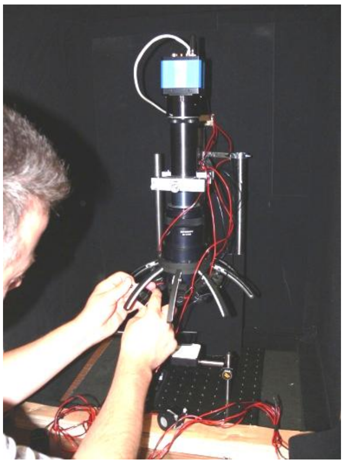

Figure 7. Combination 2.

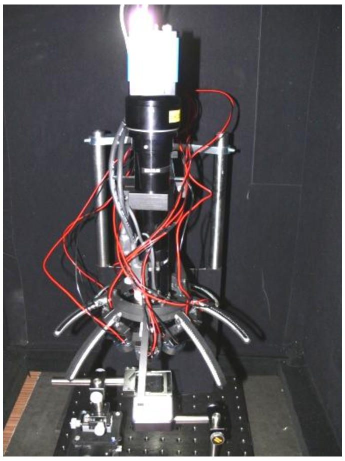

Figure 8. Combination 3, 4.

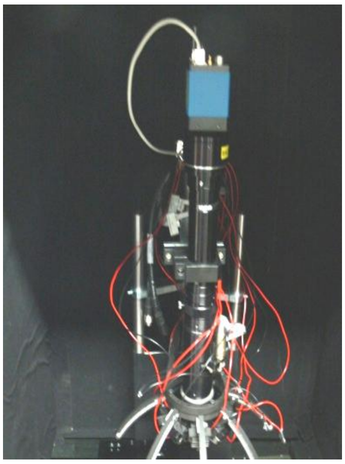

Figure 9. Combination 5, 6.

c. CCD Cameras

In this work 2 monochrome CCD cameras are used for capturing black and white images. One of them is Prosilica GE4900 16 Megapixel CCD camera, the other one is Prosilica GE2040 4 Megapixel CCD camera. The specifications of these cameras are listed in Table 3.

Table 3. The specifications of the CCD cameras.

Specifications	**GE4900**	**GE2040**
Sensor Type	Kodak KAI-16000	Kodak KAI-4021M
Sensor Shutter Type	Progressive Interline	Progressive Interline
Image Resolution	4872 x 3248 pixels	2048 x 2048 pixels
Pixel Size	7.4µm x 7.4µm	7.4µm x 7.4µm
Optical Format	35mm optical format (43.3mm physical diagonal)	21.43mm diagonal
Lens Mount	Nikon Bayonet (F-mount) - adjusTable	Nikon Bayonet (F-mount) - adjusTable
Full Resolution Frame Rate	3.35 fps	15.2 fps
Digitization	12 Bits	12 Bits

d. Resolution Test Target

Edmund Optics NT38-257 1951 USAF Resolution Target is used for the tests. Edmund Optics NT58-609 White Balance Reflectance Target is used under the 1951 USAF Resolution Test Target.

e. x-y-z Fine Positioning Stages

For x and y positioning Edmund Optics NT55-282 Solid Top Ball Bearing Stages and for z positioning Edmund Optics NT55-031 Metric Z-Axis Stage are used for positioning in three axes and alignment of 1951 USAF resolution test target at the optical axis and the working distances of the lenses.

f. Data Processing Software

The software was developed under MATLAB for the calculations of image contrast at various spatial frequencies and the MTF calculations. The gray level contrasts are analyzed on each spatial frequency of 1951 USAF resolution test target. An average profile is obtained for every selected spatial frequency region shown in Figure. 10 and Figure. 11 to determine the maximum and minimum intensity values of each frequency. These intensity values are applied to equations 2 and 5 for all spatial frequencies to get the CTF, then using Eq. 8 the MTF graphs are plotted. The software GUI was developed in MATLAB to process the images via a multi-region selection, and to calculate and plot the MTF vs. Spatial Frequencies graphs.

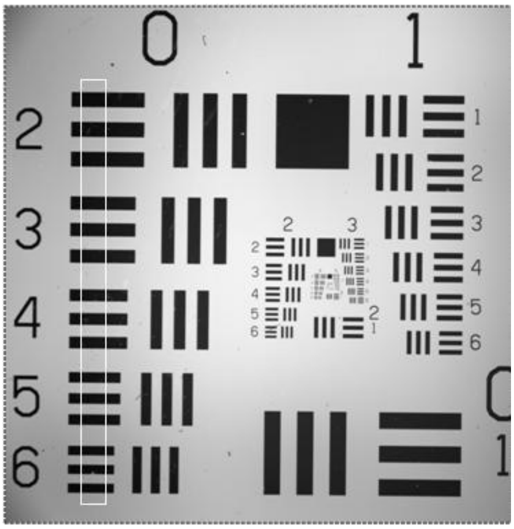

Figure 10. Representation of selected spatial frequency regions of 1951 USAF resolution test target.

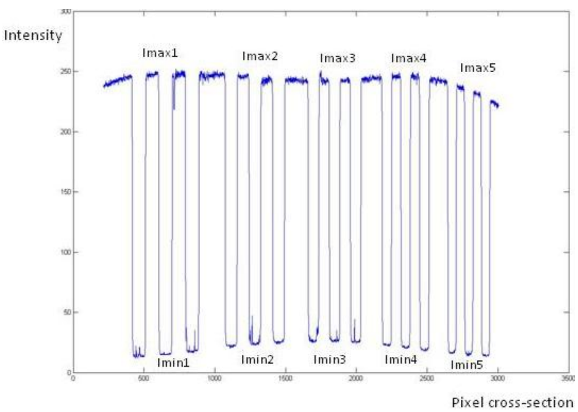

Figure 11. The maximum and the minimum intensity values obtained from the image at Figure 10.

4. RESULTS

In this work, a systematic theoretical MTF measurement approach is introduced to measure the quality of imaging systems and MTFs of six imaging system combinations are calculated and their graphics are plotted for different wavelengths. Test system is composed of illumination module, six different lens combinations, 4 and 16 Megapixel CCD cameras, USAF 1951 resolution test target, x-y-z fine positioning stages and data processing software. 8 different homogeneous light sources (Amber, Blue, Cyan, Green, Red, Red-Orange, White, and Worm-White) are used for MTF measurements. In tests, 4 different lenses and their 6 different combinations are tested. 2 fixed magnification lenses and 2 motorized zoom lenses with two lens attachments are tested. The results are represented for all combinations and maximum and minimum magnifications for combinations 3, 4, 5, 6. Resolution test target is illuminated by illumination module. Optical systems are mounted in the hole of the illumination system and the center of the optical axis. Resolution test target is placed at the center of the illumination sphere, optical axis and working distance of the lenses. Working distance of the lenses and the center of the illumination system are aligned and matched. The pictures of resolution test targets are taken by the software of the CCD cameras. These pictures are transferred to the MATLAB and processed. Using MATLAB, it is calculated the image contrast at various spatial frequencies for all imaging system combinations. The gray level contrasts are analyzed on each spatial frequency of 1951 USAF resolution test target. An average profile is obtained for every selected spatial frequency region to determine the maximum and minimum intensity values of each frequency. Using these intensity values at each frequency, CTF and MTF are found for all imaging system combinations, respectively. MTF graphs for all combinations are plotted in Figureures 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21. For most of the combinations red light gives better MTF results. For some other combinations red and red-orange lights give better MTF results. For combination 1, MTF at 100 lp/mm is measured more than %20. For combination 2, MTF at 100 lp/mm is measured more than %50. For combination 3, At minimum zoom (maximum FOV), MTF at 50 lp/mm is measured about %10, at maximum zoom (minimum FOV), MTF at 200 lp/mm is measured about %30. For combination 4, At minimum zoom (maximum FOV), MTF at 50 lp/mm is measured about %20, at maximum zoom (minimum FOV), MTF at 200 lp/mm is measured about %15. For combination 5, at minimum zoom (maximum FOV), MTF at 50 lp/mm is measured about %20, at maximum zoom (minimum FOV), MTF at 100 lp/mm is measured about %40. For combination 6, At minimum zoom (maximum FOV), MTF at 50 lp/mm is measured about %20, at maximum zoom (minimum FOV), MTF at 200 lp/mm is measured about %20.

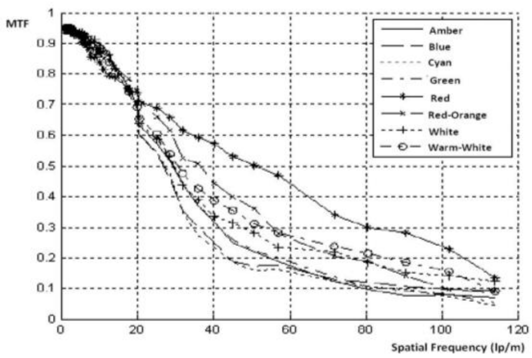

Figure 12. MTF Graph for combination 1.

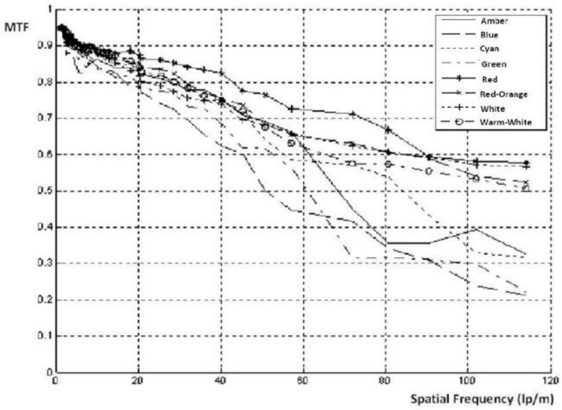

Figure13. MTF Graph for combination 2.

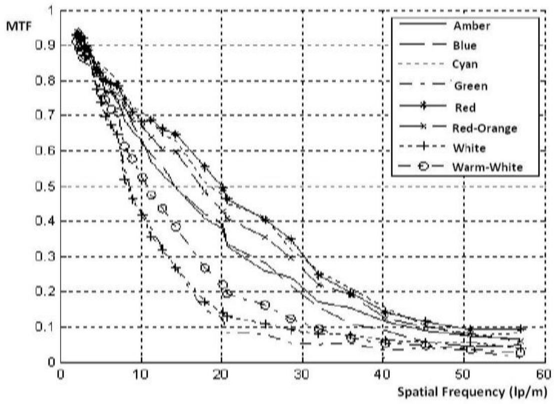

Figure 14. MTF Graph for combination 3 minimum zoom.

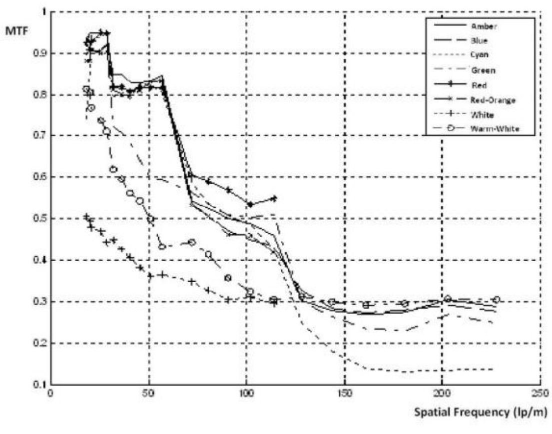

Figure. 15. MTF Graph for combination 3 maximum zoom.

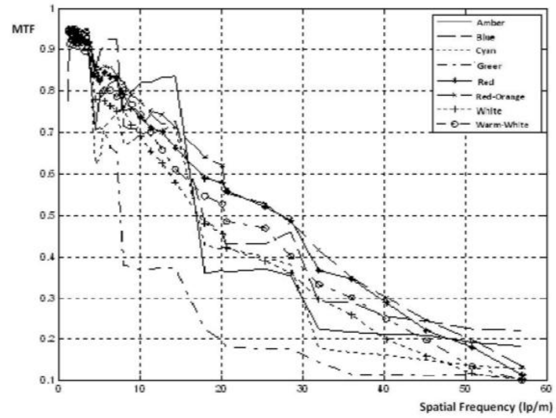

Figure 16. MTF Graph for combination 4 minimum zoom.

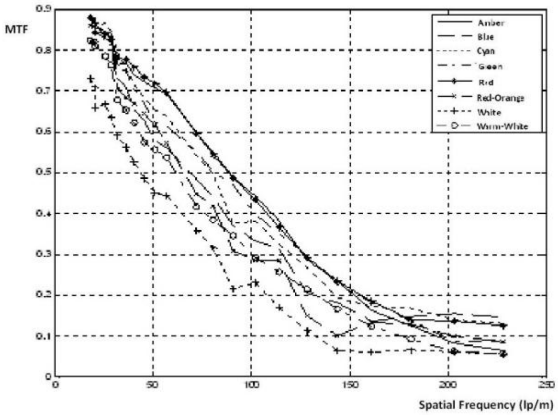

Figure 17. MTF Graph for combination 4 maximum zoom.

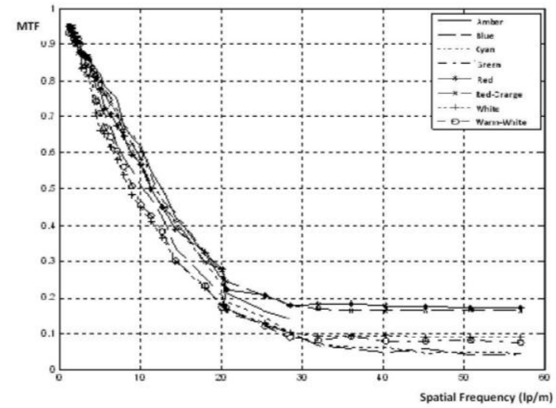

Figure 18. MTF Graph for combination 5 minimum zoom.

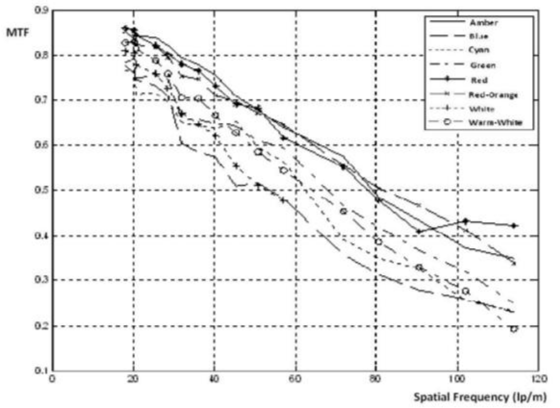

Figure 19. MTF Graph for combination 5 maximum zoom.

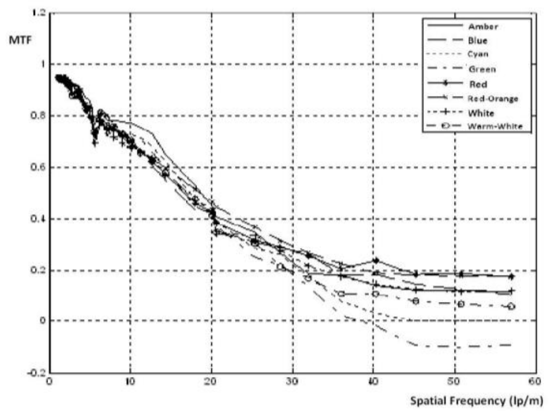

Figure 20. MTF Graph for combination 6 minimum zoom.

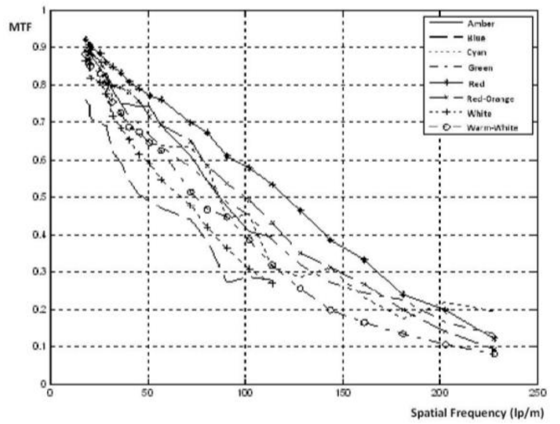

Figure 21. MTF Graph for combination 6 maximum zoom.

5. CONCLUSION

In the present work, MTFs of 4 different lenses and their 6 different combinations are measured by using 1951 USAF resolution test target. Using theoretical background, the captured images from the imaging systems are processed by the software developed under MATLAB. Then MTF graphs are plotted for the 6 different imaging systems using 8 different light sources. The present work provides a systematic theoretical study and a practical applied MTF measurement study for the imaging system quality analysis.

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