UNIVERSITY OF ROCHESTER

Design Description Document

Multispectral Imaging System Design Study

Joseph DiFabio, Jiashi Maggie Han, Angel Morales, Marissa Traina

Customer:	Dr. Roy S. Berns
Engineers:	Joseph DiFabio, Maggie Han, Angel Morales, Marissa Traina
Advisor committee:	Dr. Jennifer Kruschwitz

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Authentication Block

A Multi-spectral Imaging Device is a color accurate image capturing system, which uses multiple color channels to create a vector in color space from which the true spectral reflectance of a subject may be calculated. Such devices are useful in art analysis, archiving, and restoration. Current multi-spectral imaging devices for this application are limited in the number of channels available because they use a series of colored glass filters. This process could be made more accurate by increasing the number of channels, utilizing tunable filter technology, or by creating bandpass filters with more ideal wavelength structures for getting a variety of distinct RGB values. The design study will investigate tunable and custom bandpass filters, imaging lenses, and illumination effects in relation to creating multi-spectral images within constraints of the imaging system as specified by the customer. It is designed to assist the customer's understanding of the imaging system and the role of each component in system performance, and to guide the customer when making and implementing future design choices for the improvement of the system.

Contents

Original Product Requirement Document

(See Appendix 2)

Optical Design Study

Overview:

The customer desires to create a tripod-mounted imaging system, consisting of a high resolution, 50MP monochromatic sensor, an imaging lens, and a series of color filters attached to the front of the lens on a rotating wheel. This system will be used to obtain a series of high-quality, monochromatic images using each color filter, primarily of painted artwork. These images allow for the creation of a vector in color space, which is used to calculate the true spectral reflectance of the subject on a pixel-by-pixel basis. This allows for extremely accurate printing and archiving of artwork, and can be useful in restoring damaged paintings. This design study will investigate several aspects of this system design and present this analysis to the customer. The key aspects of this study will be an analysis of the imaging lens options, the analysis of alternate filter technologies (tunable filters or interference based filters), and the design of a tunable filter based system for validation of system performance.

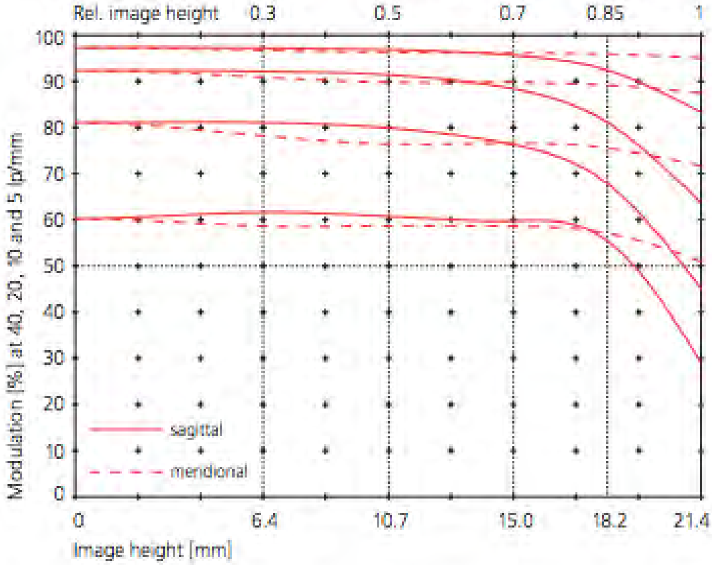
Imaging Lenses

The primary concerns when selecting an imaging lens to pair with the system include distortion and chromatic aberration. For the software to properly analyze the images captured, extremely low levels of vignetting, distortion, and chromatic aberration are allowable. It is also necessary that the lens is able to achieve focus with each of the colored glass filters in front of the lens, and it is desirable that the same focus setting is able to be used for all of the filters.

Because of the tight distortion and chromatic aberration specifications, an apochromatic enlarger lens is recommended. Enlarger lenses are typically used for the production of photographic prints from film or glass negatives. They are used as projector lenses to reproduce the negative onto paper with near perfect reproduction of the original. Because of this application, these lenses are corrected specifically to create a flat field, eliminate distortion, and to limit chromatic aberration. These lenses can be used for imaging on a sensor as well, when paired with an extension tube for focusing. To ensure the highest quality images possible, and the best chromatic aberration correction, only apochromatic models are considered.

The Rodenstock Apo-Rodagon-N 105mm was selected as the initial testing lens because of availability and meeting requirements. It was mounted to the Fingerlakes Instruments ML-50100 50 MP monochrome camera, using bellows as an extension tube, and then finding the best focus. The images captured were of much higher resolution than previous tests, and focus was obtained with all seven colored glass filters for the first time.

Modulation transfer function **Scale 10x** **f-stop 2.8**



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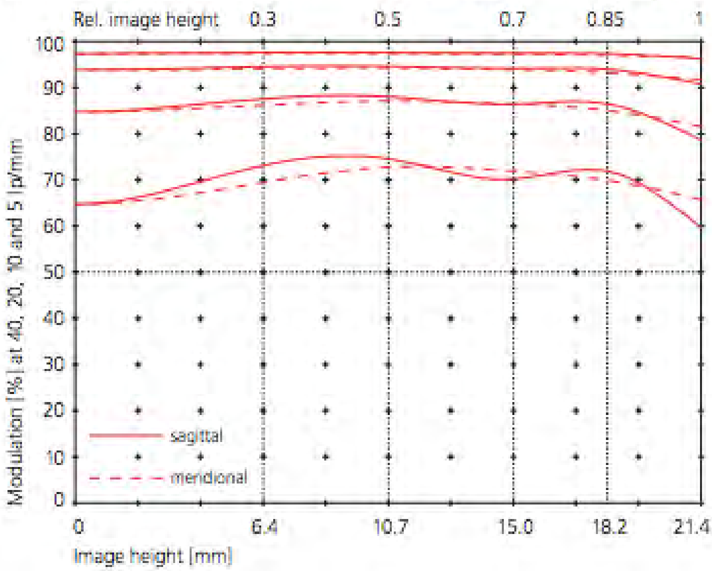
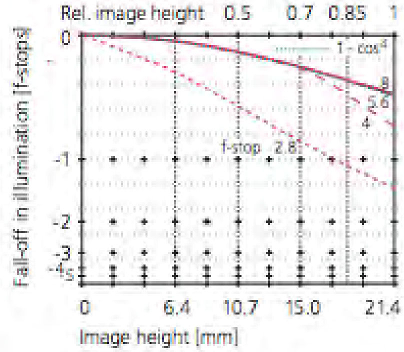
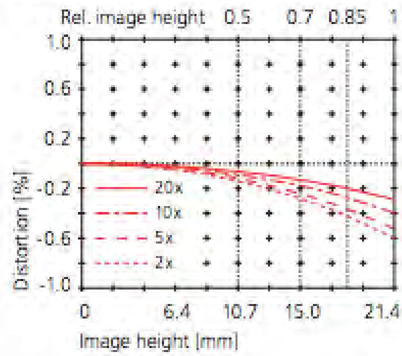


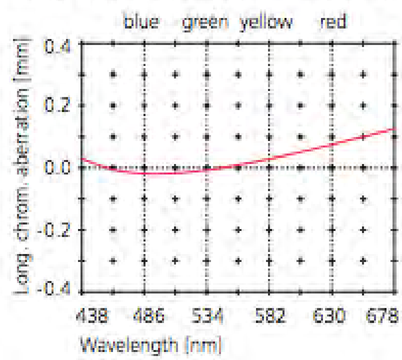
Fall-off in illumination **Scale 10x**



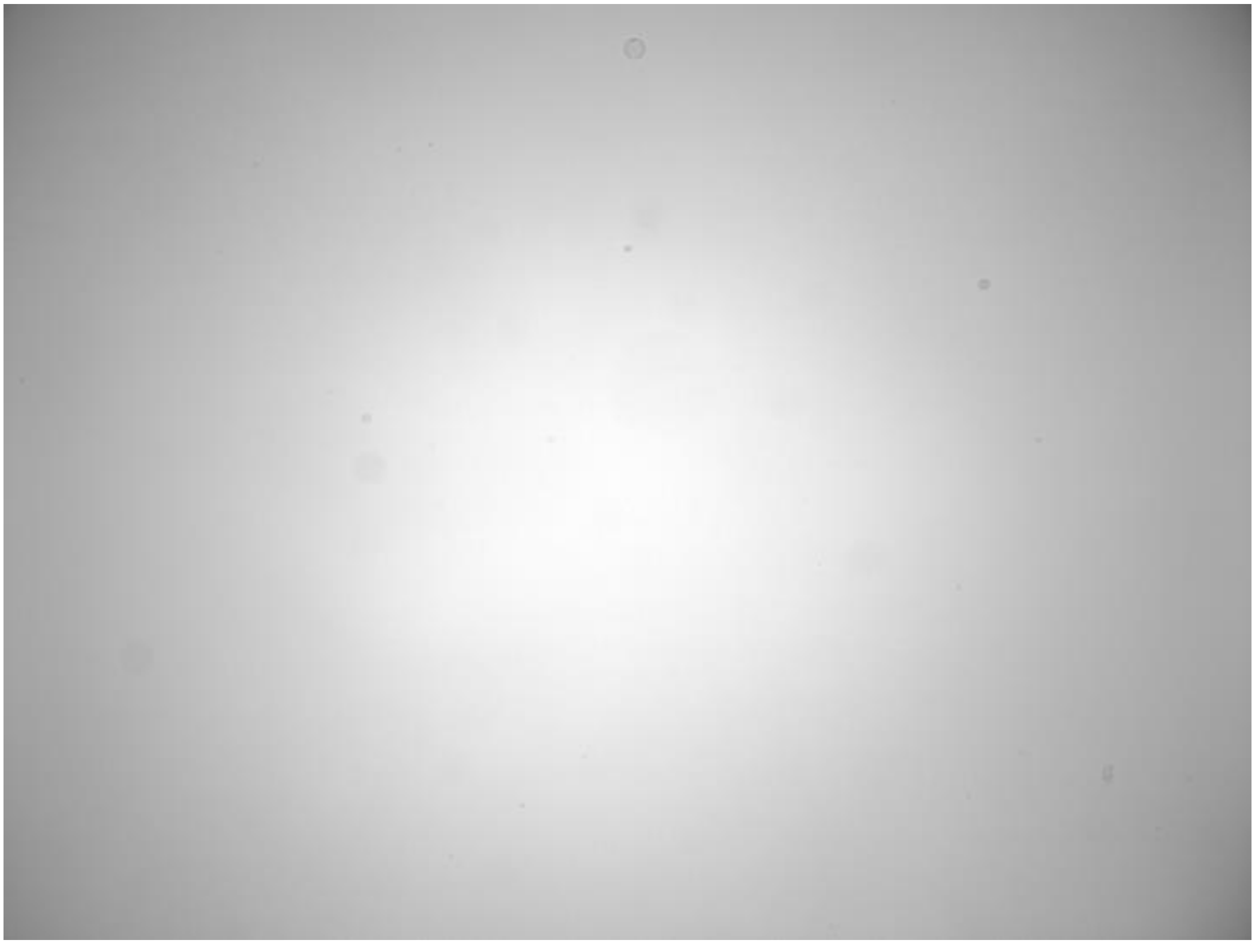
Distortion **Scale 20x ... 2x**



Long. chrom. aberration **Scale 10x**



Vignetting Issue



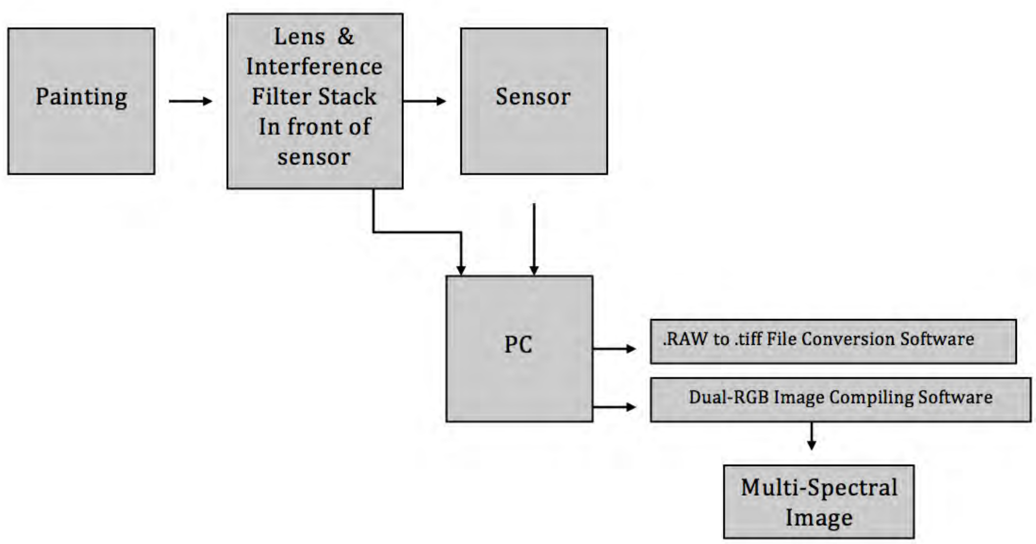
As can be seen in the flat field image above, there is a significant amount of vignetting in the system as currently set up. The system otherwise performs as intended. Because the vignetting is so significant, it is preferable to correct as much as possible optically, so the burden of correcting in software is less. Current steps being taken to ameliorate the issue include using a smaller aperture, transitioning to larger filters, and using bellows as the focusing connection between the lens and sensor. The issue could also be ameliorated by selectively using a smaller portion of the sensor (in the middle) for imaging.

A note on vignetting: There can be considered three types of vignetting contributing to this system - optical, natural, and mechanical vignetting. The optical vignetting can be remedied by stopping down the lens, and the mechanical vignetting can be remedied by ensuring that the filters are sufficiently large and no edges protrude into the field of view of the lens. The natural vignetting of the lens, however, cannot be remedied and must be corrected for in software (an existing capability of the customer).

Interference-Based Filter Design:

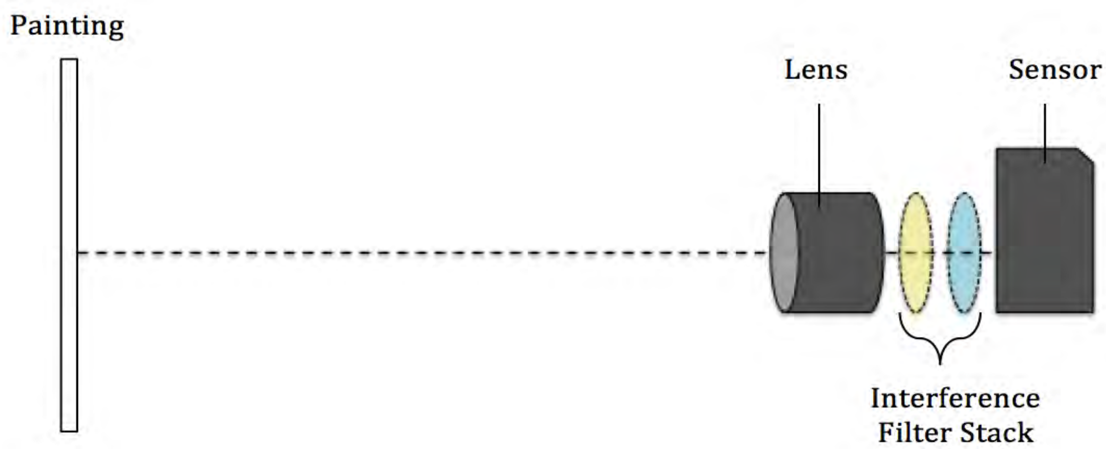
System Block Diagram:

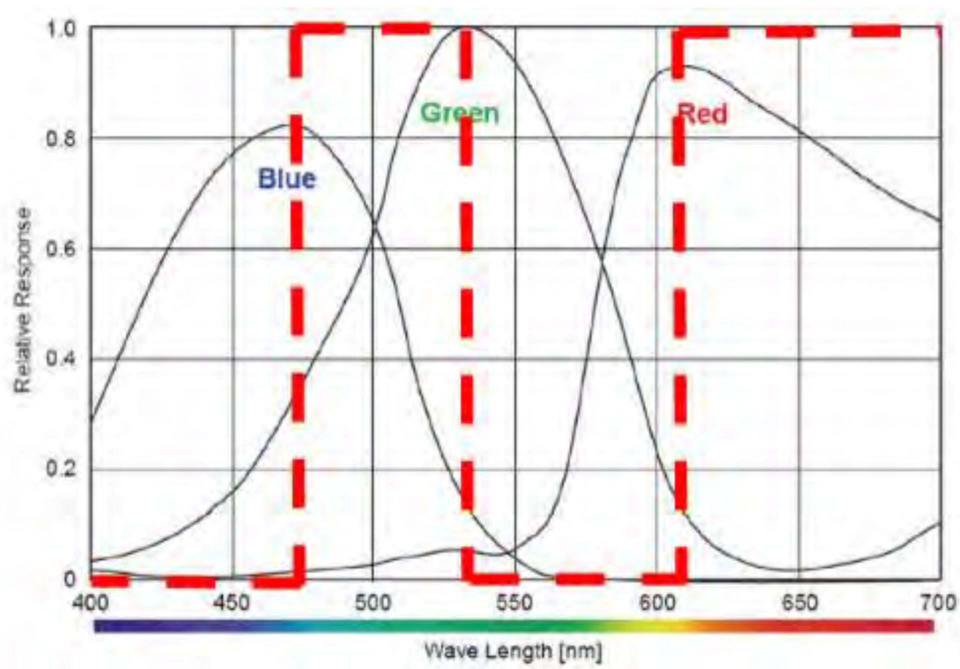
1) An optical system with thin interference filter stack in front of the sensor, which will generate a true 6-channel dual RGB image.
2) Mechanical attachment parts to connect all parts in the system.
3) Photoshop and Matlab software for analysis.



Interference filters could be employed for the system to create six color channels with two images. One slide with two different band pass filter stacks (one as characterized in the sketch below, and its inverse) would be placed directly in front of the sensor. This slide could be mechanically moved between image captures. This has the advantage of being lower cost and more compact than the colored glass filter design, and would reduce the registration errors which occur due to small differences in thickness between the colored glass filters.

These filters as designed in OptiLayer are presented below.

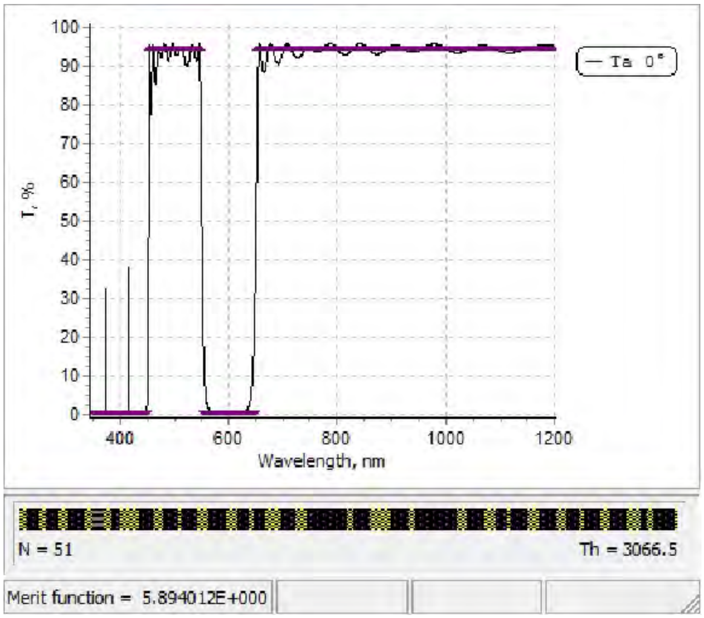


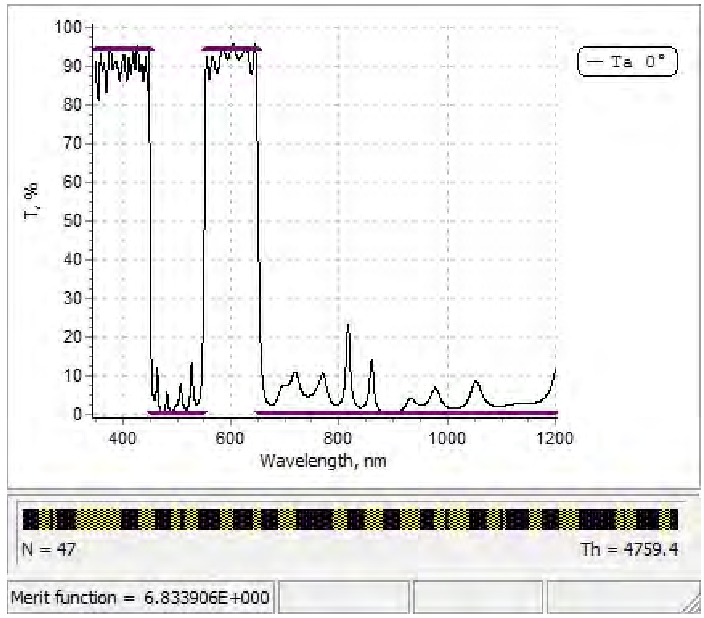


Risk Assessment:

With any interference-based bandpass filter design, input angles are a concern; as angle of incidence increases, the bandpass moves down to lower wavelengths. In the OptiLayer design shown below, steps were taken to mitigate the effect of high angles on the filters. The filters can be placed right in front of the sensor to minimize the angles of incidence on the slides.

Custom Filter Design:





Left: Transmission band: 450-550nm, 650+ Materials: SiO2 (n~1.45), TiO2 (n~2.3)	Right: Transmission band: 350-450nm, 550-650nm Materials: SiO2 (n~1.45), TiO2 (n~2.3), HfO2 (n~2.0)

**Note: The reflective regions of the two filters are not perfect to 0%, but they can be integrated and canceled in analysis calculations.

Angular acceptance range: 0-45 degrees. The bandpass information does not change significantly to affect any calculations.

Manufacturability: High. Each filter is around or less than 60 layers of films. It is an acceptable number for this application.

Alternate Tunable Filter Technologies

A number of commercially available tunable filters could potentially be implemented in the system to achieve a true spectral reflectance. This would be in the hopes of improving upon the current 7-channel system using custom, interference-based bandpass filters. The following data is shown to portray the 7-channel transmission spectra currently in use in the Munsell Color Science Laboratory setup.

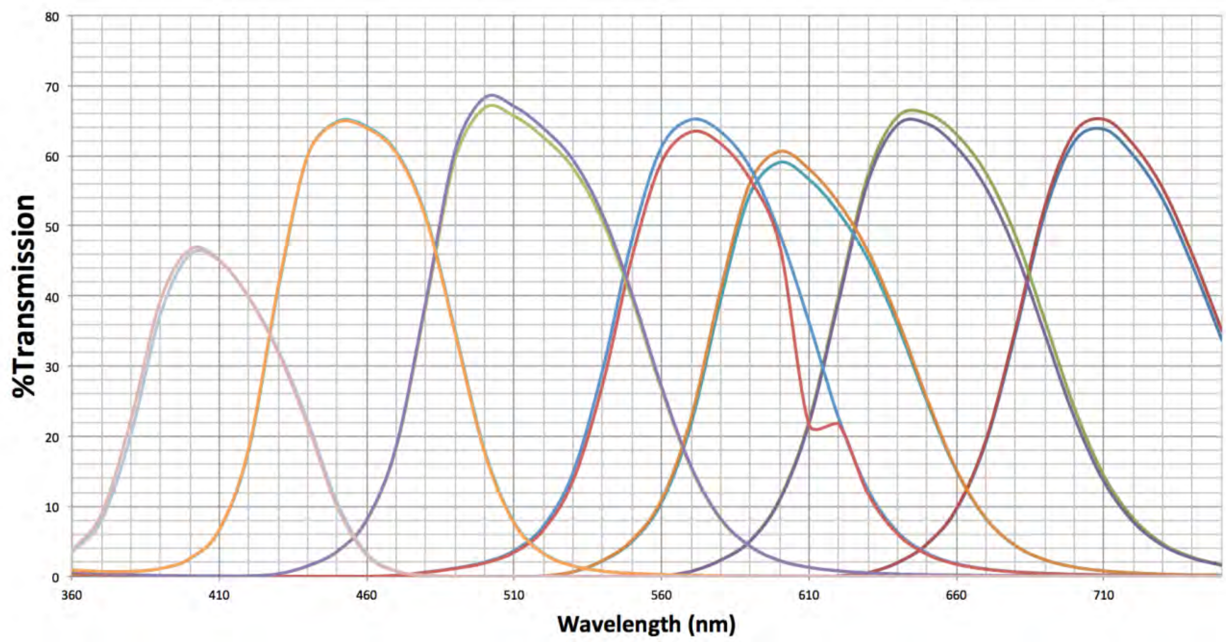
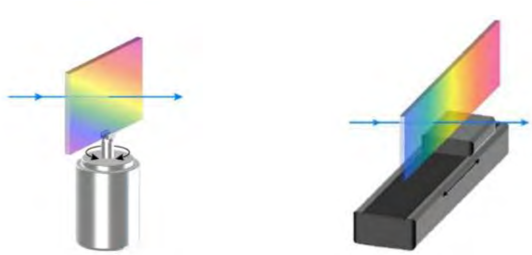


Figure 5. *The above figure plots % Transmission vs. Wavelength (nm). This data was taken using a ColorEye Spectrophotometer. Each individual peak represents the transmission data for 1 of the 7 interference-based bandpass filters.*

The main issue that arises in this system derives from the inherent sensitive angular dependence of the interference filters, which then shifts the transmission peaks. Furthermore with only 7 channels, color information is missing and we cannot confidently call this a true spectral reflectance. Our leading goals in searching for current commercially available tunable filters is to increase channels, thus creating a more continuous transmission spectrum, increase acceptance angle or rid angular dependence with absorption filter options, and improve spectral performance at the edges of the visible spectrum (in the blue and red regions).

Possible Alternative Options:

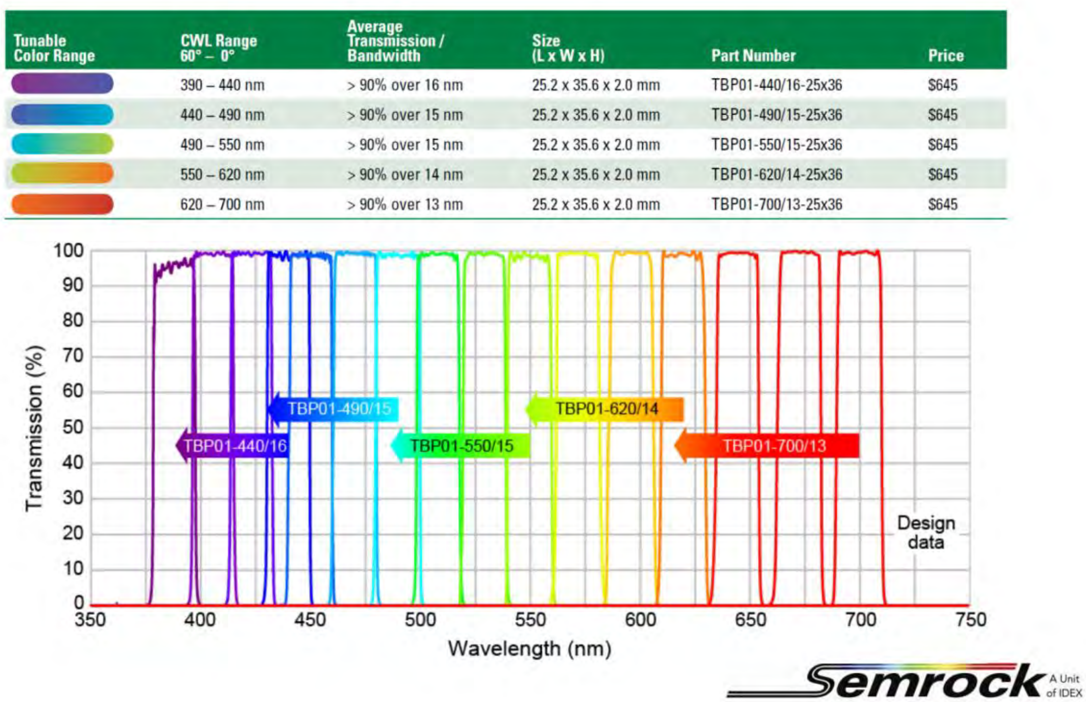
- Linear-Variable tunable filter
- Semrock VersaChrome tunable thin-film filter



Comparison Table:

Property	***LCTF***	***Linear-Variable***	***VersaChrome***
High passband transmission	***NO***	***YES***	***YES***
Top-hat passband shape	***NO***	***YES***	***YES***
Steep Spectral Edges	***NO***	***NO***	***YES***
Wide-tuning range	***YES***	***YES***	***YES/NO***
Polarization Insensitive	***NO***	***YES***	***YES***
Wide Angular Field of View	***YES/NO***	***NO***	***NO***
Price	***$9,000***	***$1,000***	***$4,000 for 5***

The above table paints the VersaChrome tunable thin film filter as the forerunner. At first glance the tunable filter technology appears to improve many areas while covering the visible spectral range with 5 separate filters.



Tunable Color Range	CWL Range 60° – 0°	Average Transmission / Bandwidth	Size (L x W x H)	Part Number	Price
	390 – 440 nm	> 90% over 16 nm	25.2 x 35.6 x 2.0 mm	TBP01-440/16-25x36	$645
	440 – 490 nm	> 90% over 15 nm	25.2 x 35.6 x 2.0 mm	TBP01-490/15-25x36	$645
	490 – 550 nm	> 90% over 15 nm	25.2 x 35.6 x 2.0 mm	TBP01-550/15-25x36	$645
	550 – 620 nm	> 90% over 14 nm	25.2 x 35.6 x 2.0 mm	TBP01-620/14-25x36	$645
	620 – 700 nm	> 90% over 13 nm	25.2 x 35.6 x 2.0 mm	TBP01-700/13-25x36	$645

The above graph represents the spectrum that can be achieved when implementing 5 of the VersaChrome filters. The VersaChrome filters are highly angularly dependent and as a technology proposes to use that to its advantage. It appears to be polarization insensitive, have high out-of-band blocking, steep spectral edges and a large aperture.

Risk Assessment:

For both alternative filters, the biggest concern is the impact of the size of the object being imaged. Since the filters are so angularly dependent there may be issues with off-axis points and limited field of view. Furthermore, although the VersaChrome tunable thin film filter set appears to be a suitable option based on the data provided by the manufacturer, there is no accessible third party data to back up the company's claims concerning their performance.

Stitching

Given that resolution is one of the most important parameters to consider in this design project, we can utilize stitching to achieve our resolution goal. In order to satisfy a requirement of 600 pixel per inch (ppi), stitching is required, in order to use the liquid crystal tunable filter. This is due to the etendue of the system and the LCTF's angular restriction. A stitching calculation shows:

Pixel Pitch: 6 microns
Target Painting Size: 609.6 x 914.4 mm
LCTF Half Field of View: 7.5 degrees
This would require 20 images with minimal overlapping.

The primary obstacles to consider when designing a precise setup of image stitching are mechanical. There are several existing mechanical systems engineered for this application. An example of a stitching mechanism is panoramic imaging. Panoramic imaging, when prepared correctly, will eliminate image distortion, allowing for accurate color analysis of large objects. An example of a panoramic system used for research of image archival is the GigaPan EPIC Pro camera mount, which comes with its own image stitching software. The price for this system is $995.

Another method of multispectral imaging archival and analysis involves translating the camera in two dimensions to scan the image as needed, or, alternatively, translating the object to achieve the same scanning effect. This solution is also primarily restricted by the precision of its mechanics.

Test Plan / Validation

There are three key aspects to the testing and validation of a multispectral imaging device. First, testing must be done to ensure that the system meets the resolution requirements (600 ppi) given by the customer. Next, the camera and lens system must be tested with a flat field to ensure that the distortion and/or vignetting in the system is minimal and can be well accounted for. Finally, the multi-spectral images obtained with the system must be compared with the results of the images obtained with the current systems in use. The new system, which provides more color channels (9 filters rather than 7), should be more accurate than the current system, especially on the edges of the visible spectrum, but also should align to a certain degree with the expected results. It is desirable that a new technique of qualifying such multispectral images is created. Such qualification tests could use tunable filter technologies, which have many color channels (about 31), but sample only a small portion of the desired FOV. This restricted FOV could be compared to that subsection of the image taken with the system under test.

"Ground Truth" Using the Liquid Crystal Tunable Filter:

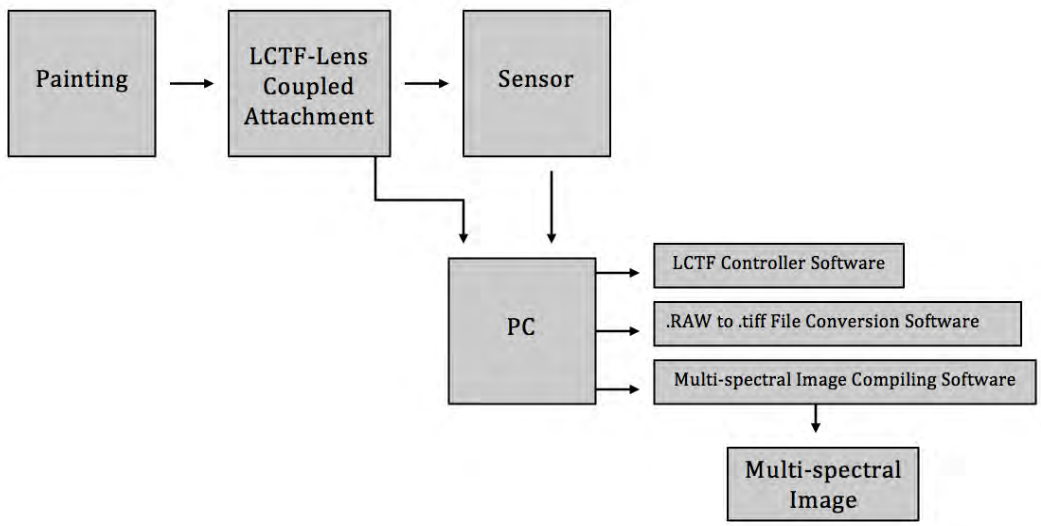
Agreement of measurements taken with these proposed systems to already-established multi-spectral imaging systems determines the usefulness and benefit of utilizing any new image archival system. In addition to the color wheel filter system used in Dr. Berns' current setup, the use of LCTF multi-spectral systems has been used for the development of archival imaging techniques and color vectors.

Despite the limited field of view of the LCTF that Dr. Berns possesses, the LCTF is still highly useful, in that it can provide up to 31 color signals, creating an extremely informative, fully characterized color space vector. Dr. Berns suggested to us that we utilize the additional color signals from the LCTF as a reference point, or "ground truth." The ground truth is the reference measurement that we take to be the most representative of the subject. Thus, we can use this ground truth as a way to test any new experimental setup for multi-spectral imaging differences.

To test the quality of a new system arrangement, the user would simply have to swap out the existing color filter system with the LCTF attachment and take a picture with the same conditions. This test would preserve the desired resolution while losing signal at the edges of the subject. For this reason, the color comparison would have to be done solely at the center of the image, with its diameter depending on the distance and size of the object. This test could be performed for any change in the archival system. Once verified, the new multi-spectral archival system could then be used repeatedly without further cross-referencing.

System block diagram:

1) Liquid Crystal Tunable Filter attached to camera sensor
2) Photograph of same subject in same conditions as previous multi-spectral imaging system
3) Photoshop software for analysis.



Transition Plans

The information generated and presented in this design study will serve to advise Dr. Berns and his staff as they move forward with their plans to upgrade their multi-spectral image capturing technologies. The final document should help close some gaps in the current understanding of his group on the optical side of the imaging equipment choices available, the filter technologies available, and what their specifications mean in terms of image quality, color accuracy, and compatibility with various imaging lenses. This document can serve as a guide for the selection of filter technologies and imaging lenses for Dr. Berns and his group.

References

http://art-si.org/PDFs/Acquisition/Roy_Berns_Final_NAS_chapter.pdf

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Sensor Specs
http://www.flicamera.com/spec_sheets/ML50100.pdf

Rodagon Lens system
http://www.rodenstock-photo.com/Archiv/e_Rodenstock_Printing_CCD_43-62__8230.pdf

Alternative Tunable Filters
https://www.semrock.com/Data/Sites/1/semrockpdfs/tunablefilters.pdf

Stitching
https://www.jvrb.org/past-issues/4.2007/1275/figure02.jpg

GigaPan EPIC Pro Camera Mount
http://www.gigapan.com/cms/manuals/epic-pro-introduction

Appendix 1: Customer Document

Multispectral Imaging:

Optical Design Considerations

Joseph DiFabio, Jiashi Maggie Han, Angel Morales, & Marissa Traina
University of Rochester, Institute of Optics

TO: Dr. Roy S. Berns
RE: Multi-spectral imaging device improvements

Abstract

The following design study aims to support decision-making in key optical design choices vital for improving current multi-spectral imaging technologies. The central focus in the study will be improving a tripod-mounted imaging system, consisting of a high resolution, 50MP monochromatic sensor, an imaging lens, and a series of color filters attached to the front of the lens on a rotating wheel. This system will be used to obtain a series of high-quality, monochromatic images using each color filter, primarily of painted artwork. These images allow for the creation of a vector in color space, which is used to calculate the true spectral reflectance of the subject on a pixel-by-pixel basis. This allows for extremely accurate printing and archiving of artwork, and can be useful in restoring damaged paintings. This design study investigates several aspects of this system design and aims to present further analysis. The major aspects of this study will be analysis of the imaging lens options, analysis of alternate filter technologies i.e. tunable filters or interference based filters, and the design of a tunable filter based system for validation of system performance.

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Glossary of Terms

Aperture Stop - The limiting aperture in the optical system, which will first clip rays as the input angle in increased. The aperture stop limits the amount of light that will be gathered by an optical system.

As the aperture stop changes in size, the **f/number** of the system changes. The f/number is the ratio of the focal length of the lens to it's entrance pupil diameter. As the size of the aperture stop is decreased, less light will be allowed into the system and the f/number will increase. This is sometimes referred to as the **speed** of the lens. "Faster" lenses have lower f/numbers, therefore larger relative apertures.

The size of the aperture has an effect on the **depth of field**. Smaller apertures (higher f/numbers) yield a larger depth of field, allowing objects at a wider range of distances to be in focus at the same time. This is specifically applicable to the use of color filters because it can also allow a wider range of colors to be in focus on a monochromatic sensor.

Stopping down the aperture (increasing the f/number by making the iris at the aperture stop smaller) can also reduce the visible effects of optical aberrations and reduce the amount of vignetting in the system, at the cost of light level.

Chief Ray - In geometrical optics, the ray which begins at the edge of the object and passes through the center of the aperture stop, at the optical axis.

Diffraction Limited Aperture - The diffraction limited aperture (DLA) is often given as a specification for a given imaging lens (especially when designed for use with a given sensor). This is not, however, a specification for the "ideal" aperture at which to use the lens. Rather, it simply defines mathematically the aperture size at which diffraction begins to visibly impact the sharpness of the image at the single pixel level. This does not mean that the system cannot be used at a smaller aperture, it just shows that there is some tradeoff happening (as there always is when selecting which aperture size/f number to use).

Using an aperture smaller than the specified DLA will sacrifice some amount of fine pixel sharpness in exchange for increased depth of field and decreased vignetting. In general, higher density pixels in the sensor or display monitor will allow somewhat smaller apertures than the specified DLA. Higher resolution sensors will also produce higher resolution, more detailed images at smaller apertures than the DLA, as compared to sensors with larger pixels, despite some amount of overfilling of the pixel size. This is true until a "diffraction cutoff" spatial frequency is reached in object space. In other words, narrower apertures may be used and imaged onto high resolution sensors for objects that do not have extremely fine spatial frequency details, with only the tradeoff of reduced light.

In general, these tradeoffs are best found experimentally for a specific system. Image analysis will show how much loss of sharpness is acceptable.

Etendue - a purely geometrically quantity, etendue is a property of light propagating in an optical system measuring how spread out the light is both angularly and in space/area. This can be defined from the perspective of the source (area of source multiplied by solid angle subtended by the entrance pupil of the optical system as seen by the source) or, equivalently, from the perspective of the optical system (the area of the entrance pupil multiplied by the solid angle subtended by the source as seen from the entrance pupil).

Etendue is always conserved as light travels through free space, and is conserved as it propagates through an optical system, if all reflections and refractions are perfect. Imperfect reflections or refractions result in increased etendue. Therefore, in real optical systems, the etendue of the output is always the same or higher than that of the input. This is related to the Optical invariant.

This property explains why systems cannot be created with arbitrary fields of view and resolutions. This can be thought of as similar to the law of conservation of energy. As the area of the spot focused by an optical system gets smaller (increasing the resolution), the angular content of that beam spreads out, and vice versa. This relationship cannot be broken.

Marginal Ray - In geometrical optics, the ray which begins where the object crosses the optical axis, and which passes through the aperture stop right at the edge.

Optical Invariant - Sometimes referred to as the Lagrange Invariant, this is a simple measure of the light propagating through an optical system, using the marginal and chief rays of the system. It is defined by:

$$H = n\underline{u}y - nu\underline{y}$$

Where:
y = marginal ray height
u = marginal ray angle
$\underline{y}$ = chief ray height
$\underline{u}$ = chief ray angle
n = refractive index

This Optical invariant is held constant in any optical system, at any point of refraction or reflection. The square of the quantity H is directly proportional to the throughput of the system.

Vignetting - The reduction of image brightness at the periphery compared to the center. There can be considered three main types of vignetting:

Optical Vignetting - Exists in all lenses. Can be remedied by stopping down the system. This effect is illustrated by the image below. The tilting of the lens shows the perspective of light entering the aperture at a higher angle. The reduced apparent size of the aperture limits the amount of this light that will be gathered at the periphery of the image. This type of vignetting can be easily seen in out of focus images because a "cat's eye" blurring effect, which mirrors the apparent shape of the aperture, is created away from the optical axis.

Mechanical Vignetting - Caused by mechanics or filter edges protruding into the field of view of the lens. This directly blocks light from the periphery of the FOV from entering the system. The system should be set up so that this is avoided.

Natural Vignetting - Natural light falloff which is inherent in every lens. It is proportional to cos^4 light falloff in image space. This type of vignetting cannot be mitigated for a given lens. Well-designed lenses with smaller field of view tend to have less natural vignetting.

Optical Design Study

Overview

This design study is intended to be an instructive document for the customer, Dr. Roy Berns, and his team as they make design choices for the continual improvement of the overall multi-spectral imaging system. It will serve as a reference for the relevant optical specifications of each component of the system, and communicate how each of these specifications impacts system performance.

The document will be a resource for Dr. Berns to use as the system evolves and expands in its capabilities for spectrally accurate archiving of painted artwork.

Multispectral Imaging Systems

A multispectral imaging system design for art archiving purposes must include these four components: lighting, an imaging lens, a detector, and most importantly a means of wavelength selection. In this design study, the focus will be on selecting imaging lenses and a means for wavelength selection along with any implications that result from these two decisions.

Imaging Lenses

When selecting imaging lens systems to pair to the detector being used, the primary focus will be selecting lenses having low distortion and low chromatic aberration. While commercial lens products will already be well-corrected for distortion and chromatic aberration, the addition of new elements into the system -- such as color filters, liquid crystal tunable filters, interference-based filters, etc. -- will alter the performance of the lens system.

For example, the addition of various color filters can adjust the focal point of the image from the lens systems. A red color filter may yield a perfectly acceptable image quality, but using a blue color filter may adjust the focus of the lens considerably, causing a blurred image when there was previously a perfect one. Additionally, using color filters with apertures smaller than the lens' aperture will produce a loss in signal near the edges of the detector, causing vignetting. Furthermore, the use of an element such as a liquid crystal tunable filter yields a different, stricter angular dependance on the system as a whole, due to the angular acceptance of the liquid crystal tunable filter being a limiting factor. All of these effects, and more, will be expanded upon in further sections.

Due to the tight distortion and chromatic aberration specifications necessary for high-quality multi-spectral imaging, an apochromatic enlarger lens is desirable. Enlarger lenses are typically used for the production of photographic prints from film or glass negatives. During the process, they essentially "project" the negative onto a surface that will then reproduce the image desired. This application requires creation of a flat field -- to eliminate distortion effects -- and extremely low amounts of chromatic aberration to perfectly reproduce the negative's image. When paired with an extension tube for focusing, these enlarger lenses can image objects onto a sensor. To ensure the highest quality images possible with the best chromatic aberration correction available, only apochromatic models of enlarger are considered.

The Rodenstock Apo-Rodagon-N 105mm lens was selected as the initial testing lens because of availability and because it met specifications. It was mounted to the Finger Lakes Instruments ML-501000 50 MP monochromatic camera, using bellows as an extension tube. The nest focus was found thereafter. The images captured had higher resolution than previous tests, and focus was obtained with all seven colored glass filters for the first time.

Filter Technologies

Wavelength Selection Options

Wavelength Selection through Illumination

The following is a bulleted summary of the positive and negative implications of using illumination for wavelength selection:

- Filtered illumination and image capture with monochrome camera
- Advantage of economic light exposure since narrow wavelength range is incident
    - Important for light sensitive materials
- Advantage of using any available off-the-shelf monochrome camera and lens system
    - Disadvantage-->such cameras have significant chromatic aberration resulting in registration issues

Wavelength Selection of Reflected Light

The following technologies utilize filtering of the light already incident on the artwork. This is the method predominantly used by the Munsell Color Science Laboratory.

Current System: *7-Channel Filter Wheel*

Overview

- Set of custom interference-based bandpass filters
- High spectral range with narrow-band width
- Disadvantage: high angular dependence
    - Transmission peak shifts
- No image scaling necessary when chromatic aberration is minimized by lens
- Poor spectral performance at the edges of the visible spectrum
- Not a true spectral reflectance: lacking continuity

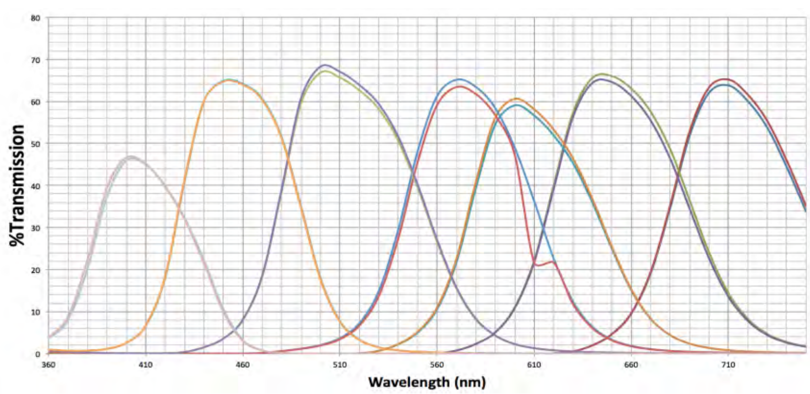


Figure 1. *The above figure plots % Transmission vs. Wavelength (nm). This data was taken using a ColorEye Spectrophotometer. Each individual peak represents the transmission data for 1 of the 7 interference-based bandpass filters.*

Alternate Options: *Tunable Filters*

Property	LCTF	AOTF	Linear-variable
High passband transmission	−	○	+
Top-hat passband shape	−	−	○
Steep spectral edges	−	−	−
Wide tuning range	+	+	+
Polarization insensitive	−	−	+
Wide-angular field of view	○	−	−
Price	***$9,000***	***$2,000***	***$1,000***

***Stitching methods must be implemented to meet resolution requirements with current tunable options*

By taking care in the optical design it is possible to use LCTFs and AOTFs to produce high quality images that are not shifted between wavelengths.

LCTF

The following is a bulleted summary of the positive and negative implications of using a liquid crystal tunable filter for wavelength selection:

- Electrically tuned filter with tuning speed on order of tens to hundreds of milliseconds
    - Can tune up to an octave between
- Bandwidths of filters are fixed and increases with central wavelength
- Transmission efficiency decreases with decreasing wavelength resulting in low blue response

- Polarization sensitive→ maximum throughput is 50%
- Generally have larger aperture and angular field of view compared to competing tunable filter technologies

AOTF

The following is a bulleted summary of the positive and negative implications of using a acousto-optical tunable filter for wavelength selection:

- Tuned by changing frequency of waves→ operates between 350-5000 nm
    - Tuning speed on order of hundred microseconds
- Volume diffraction grating
- Polarization sensitive→ possible to recombine orthogonally polarized diffracted beams to increase overall throughput
    - Unlikely that high optical quality with be maintained
- Bandwidth can be tunable-->minimum achievable wavelength increases with wavelength
- In general, have higher throughput compared to LCTF, however smaller aperture and field of view.

Other Tunable Options

- Linear-variable tunable filter
    - Outlined in above table→ could be viable option however would require x-y mechanical mount along with a potential need for stitching
- Fabry-Perot etalon
    - Wavelength tuning acheived through mechanically changing distance between mirrors using piezo-electric transducers
    - Large aperture, small angular field of view
- Fourier Transform Michelson Imaging Interferometer
    - Essentially performs FTIR spectroscopy for a number of spatial pixels simultaneously

Stitching

Stitching can be an extremely useful imaging process to obtain high-resolution images of large objects -- such as, in this case, large-format canvas paintings. Given that resolution is one of the most important parameters to consider in this design project, we can utilize stitching to achieve our resolution goal. We can also use stitching to examine the ground truth of a smaller area of the painting.

In order to satisfy a requirement of 600 ppi, stitching would be required, if use of the liquid crystal tunable filter were desired. This is due to the LCTF's angular restriction. An example of a stitching calculation follows:

Pixel Pitch: 6 microns

Target Painting Size: 609.6 x 914.4 mm
LCTF Half Field of View: 7.5 degrees
This would require about 20 images without overlapping.

In practice, a recommended technique for using stitching with minimal issues would be panoramic imaging. Panoramic imaging, when prepared correctly, will eliminate image distortion, allowing for accurate color analysis of large images. An example of a panoramic system used for research of image archival is the GigaPan EPIC Pro camera mount, which comes with its own image stitching software.

Another method of multi-spectral imaging archival and analysis involves translating the camera in two dimensions to “scan” the image as needed -- or, alternatively, translating the object to achieve the same “scan” effect. This method is typically used for smaller-scale objects, where the maximum distance to “scan” may be in the range of 12 inches. This constitutes an issue for larger format paintings, suggesting that the system with the highest ease-of-use would be the panoramic imaging system.

Vignetting

The amount of vignetting is too significant to correct in software alone in the current setup. The system otherwise performs as intended.

Possible Causes & Solutions

- Optical → stopping down the lens
- Mechanical → preventing filters from protruding into the field of view
- Natural → can be fixed by software only

Improvement Methods:

- Using a smaller aperture → longer exposure time
- Transitioning to larger filters → higher cost for filters
- Using bellows as the focusing connection between the lens and sensor
- Selecting a smaller portion of the sensor (in the middle) for image analysis

References

http://art-si.org/PDFs/Acquisition/Roy_Berns_Final_NAS_chapter.pdf

http://www.flicamera.com/spec_sheets/ML50100.pdf

Sensor Specs
http://www.flicamera.com/spec_sheets/ML50100.pdf

Rodagon Lens system
http://www.rodenstock-photo.com/Archiv/e_Rodenstock_Printing_CCD_43-62__8230.pdf

Alternative Tunable Filters

http://web.media.mit.edu/~gordonw/courses/ComputationalPlenopticImaging/CPICourseNotes.pdf

http://link.springer.com/article/10.1007/s00339-011-6689-1/fulltext.html

https://www.semrock.com/Data/Sites/1/semrockpdfs/tunablefilters.pdf

Stitching

http://chsopensource.org/panoramic%20multispectral%20imaging.pdf

http://www.jcms-journal.com/articles/10.5334/jcms.1021224/

https://www.jvrb.org/past-issues/4.2007/1275/figure02.jpg

http://www.resonon.com/Products/benchtop_system.html

Appendix 2: Original PRD

Product Requirements Document

Multi-spectral Imaging Device

Customer: Dr. Roy S. Berns
Engineers: Joseph DiFabio, Maggie Han, Angel Morales, Marissa Traina
Advisor committee: Dr. Roy S. Berns (have met with), Prof. Jennifer Kruschwitz, Samuel Steven (have met with)

Contents

Revision History

Rev	Description	Date	Authorization
A	Initial PRD based on customer presentation	10/27/15	MT
B	PRD Version 2 based on new customer meeting	11/1/15	MT
C	PRD Version 3 based on second meeting with customer	11/15/15	MT
D	PRD Version 4 for Final Class Presentation	12/1/15	MT
E	Final PRD Version 5 for Submission	12/10/15	MT

Statement of Advisors

The Multi-spectral Imaging Device project is a senior design driven color accurate image capturing system. As such its design inputs were derived from our interactions with our project advisors, Dr. Roy S. Berns, Prof. Jennifer Kruschwitz, and Samuel Steven.

Team Member Responsibilities

Team Member	**Responsibility**
Joseph DiFabio	• Scribe • Optical Design
Maggie Han	• Project Coordinator • CAD - Mechanical
Angel Morales	• Customer Liason • Testing & Modeling
Marissa Traina	• Document Handling • Colorimetry

Vision

This product is envisioned as a tripod-mountable camera working with an attached Liquid Crystal Tunable Filter (LCTF) and lens system in order to obtain high-quality, monochromatic images, primarily of painted artwork. A series of these images will be obtained by adjusting the wavelength filter on the LCTF. Having these images will enable us to create a vector in color-space that can be used to capture the true color of the various artwork, allowing for improved archival and reprinting abilities. This product is also aiming to be low-cost, and as a result, will seek to utilize already-existing camera models, lens attachments, and LCTFs so that this system can be easily reproducible.

Environment

The system is meant to be used in a lab or studio type environment. The device should be designed for use at approximately 40-100 degrees F, and so that condensing does not occur at any level of humidity on this temperature range. Since this product should be constructed with commercially available components, these standards will be met according to the specifications of these components.

The lighting which the customer intends to use with this device is established as common flash bulbs used in photography - customer states that lighting design is beyond the scope of the project.

Regulations and Risk Factors

Due to the primary focus of utilizing commercially-available technology (to reduce costs), the resulting product will adhere to the laws and regulations of the components. No alterations will be made which risk the safety of the user or which violate OSHA regulations.

Product Requirement Document

The following details describe the requirements for the end product.

First and foremost, the resulting imaging system should aim to be composed of already-available camera models (ideally, the Canon EOS 5D Mark III, as it is the one Dr. Berns currently uses), lens attachments, and Liquid Crystal Tunable Filters (LCTFs).

The system will aim to eliminate all vignetting from the system. The system, when used with the LCTF, contains some vignetting, thus losing valuable color information in each image captured. A pseudo-telecentric system (in image space) in front of LCTF is being considered to meet this requirement. This setup could also help to limit the incoming angle variations.

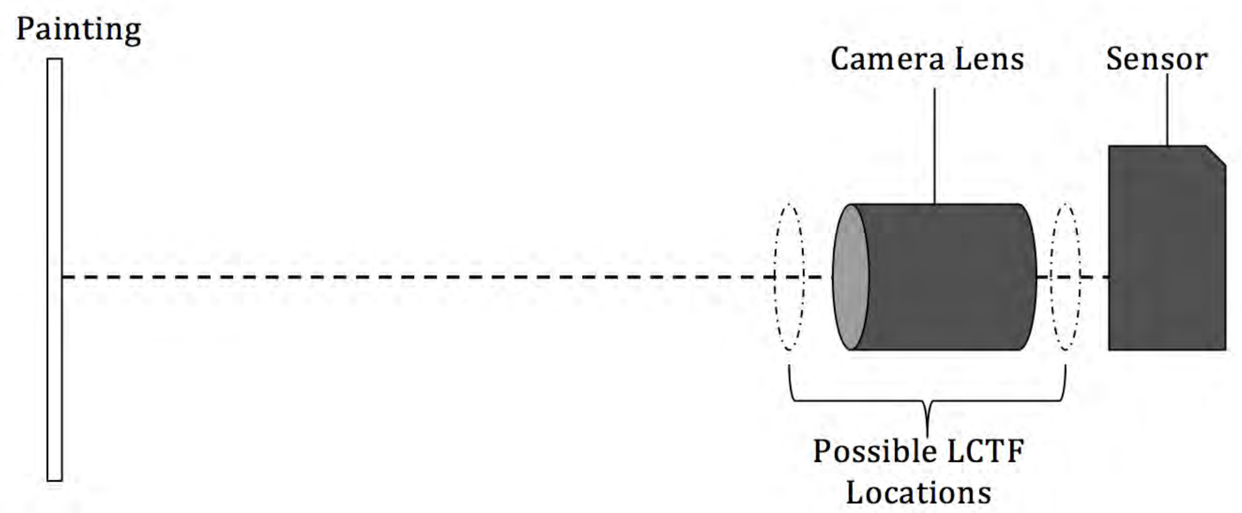
The currently available component is the monochromatic sensor from the Canon EOS 5D Mark III DSLR camera. It has approximately 24.3 megapixel (effective: 22.3 megapixel) with 6.25 um pixel size. The sensor size is approximately 36*24mm.
The target paintings are primarily 24 x 36’’ in size (~609.6 x 914.4mm).

Want:
Prototype + documents for customer use. Ideally, documents would instruct a user to assemble a similar system using only commercially-available components.

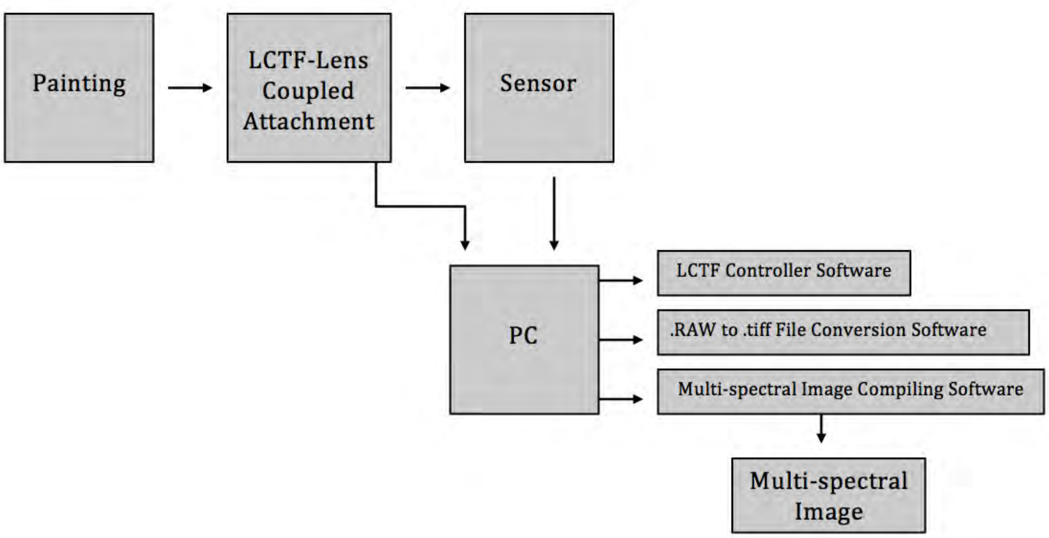
The object distance is approximately 2000mm (object to first surface).

Budget: < $4,000

Rough sketch of system:



Block diagram of system:



**Only responsible for designing LCTF-Lens Coupled Attachment in system*

Table of Relevant Specifications		
Specification	**Value**	**Comments**
F/#	≥ 8	Calculated through Etendue
EPD	dependent on EFL	Entrance Pupil Diameter
EFL	85 mm	Capturing the entire painting
	300mm	Meeting the resolution requirement
Wavelength	410-720 nm	Multiple images acquired as LCTF is tuned to pass different wavelengths in this range at 10 nm intervals.
Diagonal Full Field of View	31 degrees	
Resolution	600 pixels per inch (25.4mm)	Stated as "desirable" by customer, in object space
LCTF Thickness	38.1 mm (1.5 in.)	
LCTF Diameter	35 mm	
Working Distance	2 - 5 m	
Angles of Incidence on LCTF	≤ 7.5 degrees	Half angle, Based on angular sensitivity of LCTF
Relative Illumination	≥90%	at outermost edge of 24x36" painting
Sensor Pixel Pitch	6.25 um	Center - to - center

Not Responsible

This design project does not encompass the following:

- Illumination design (Xenon strobes)
- MATLAB code for spectral analysis of images

Options for Customer

Due to etendue restrictions, which cannot be avoided, it is not possible to achieve all of the specifications desired for this project. Specifically, the FOV and resolution specifications are at odds, and one or the other must be sacrificed. For this reason, we will present several options. We recommend sacrificing the FOV to achieve the resolution and angular requirements of the project, and to stitch several images (up to 15) together to analyze the entire painting.

1. Updating the sensor and lens:
    a. Upgrade to a Canon EOS 5DS, 50 MP sensor, which contains a smaller pixel size of 4.14 microns - $3599 from Canon
    b. Canon EF-S 18-200mm f/3.5 IS lens set @ 200mm - $699 from Canon
    c. This option achieves the desired resolution at an object distance of 2m. The FOV is 10.35 in.
    d. Note: Bayer pattern must be removed - added cost and unreliable quality

2. Upgrade of just lens - FFL
    a. Canon EF 300mm f/4L IS lens - $1299 from Canon
        i. This achieves the desired resolution at an object distance of 2m. The FOV is 11.06 in.
    b. Canon EF 70-300mm f/4-5.6 IS USM - $649
        i. FOV = 11 in.
    c. Canon EF 75-300mm f/4-5.6 III - $199
        i. FOV = 11 in., less well corrected but might be sufficient

Customer Feedback:

The customer has stated a preference to avoid option 1 listed above, as the added expense of the camera upgrade is not worth the return on performance. He is open to limiting the field of view, however, as stated in option 2. He would like us to investigate making small changes to the system so that the FOV is slightly larger and resolution is sacrificed somewhat. This can be accomplished with the system descr ibed, but by simply increasing the object distance. This must be described in detail, along with the effect on resolution, in the documentation provided with the prototype device.

Timeline

Timeline	
By 12/11 (Final PRD Submission)	• Further characterize liquid crystal tunable filter for final first order specs • Meet with Julie Bentley & Samuel Steven to discuss final first order lens design specifications • Present and confirm updated product requirement document with Dr. Berns • Further finalize Spring 2016 Schedule
January	• Create our commercial product wish list • Approve pricing and design options with customer • By end of month purchase most promising design options (2 most promising if the budget can account for it)
February	• Receive products and assemble initial test design • Begin testing setups and determine performance • Finalize mechanical mounting design • Order Mounts
March	• Assemble Final Design • Test Final Design for quality assurance • Create instructional documents for future customer use and ease of reproduction
April	• Cushion time for schedule changes • Present final product to customer

References

"Canon EOS 5D Mark III Specifications." *Canon.com*. Canon. Web. <http://shop.usa.canon.com/shop/en/catalog/eos-5d-mark-iii-body>.

"Verispec Liquid Crystal Tunable Filter Data Sheet." Perkin Elmer. Web. <http://www.perkinelmer.com/CMSResources/Images/44-140156DTS_010053A_01_VariSpec_DTS.pdf>

“Canon EOS 5DS DSLR Camera Specifications.” Canon.com. Canon. Web. <http://shop.usa.canon.com/shop/en/catalog/eos-5ds>.

“Canon EF 70-300mm f/4-5.6 IS USM” *Canon.com*. Canon. Web. <https://www.usa.canon.com/internet/portal/us/home/products/details/lenses/ef/telephoto-zoom/ef-70-300mm-f-4-5-6-is-usm/!ut/p/z1/hY_LDoJADEW_hQ9oWgF5LHnEgAGNmOg4G8NiQBKGIYIu-HpH48YYsbv2nqanyJEh78p7U5djo7qy1f2JO-d8l3hJGlHmeUVIQR7TarGzzW1m4vEfwHVMPyogXL-AmX1tYF7zKK-R9-V4gaarFLJWdIMYkIkK2Sha0V_UqGBSSj5n4BJYRFJCBTYswYFmgNsgtS3_vEeF71LgxE7ib0JKU_sLOIS2Bvw4sszV0_kNzLzUSzZlQbVPa8N4AK1mhgk!/dz/d5/L2dBISEvZ0FBIS9nQSEh/>

“Canon EF 75-300mm f/4-5.6 III” *Canon.com*. Canon. Web. <https://www.usa.canon.com/internet/portal/us/home/products/details/lenses/ef/telephoto-zoom/ef-75-300mm-f-4-5-6-iii/!ut/p/z1/hY_PDoIwDIefxQdoWhEGHPkTAwY0aqJzF8Nh4BJgRBYPPL3TeDFG7a39fU2_okCOoq9uqqmM0n3V2v4k2LncZkGWJ1QEwS6mqExpOd-6zqZw8PgPEDamLxURrp7Aj31r4FzLpGxQDJW5gOprjbyV_ShH5LJGbmQrh4s2Giatu8cMfA8WRF0HNbjgAQOllFUV78doF_oUsZRl4TqmPHc_gEPsWiBMk4WzfAi_gB__DB2fiqje581sdgcRtpKn/dz/d5/L2dBISEvZ0FBIS9nQSEh/>

“Canon EF 300mm f/4L IS USM Lens” *Canon.com*. Canon. Web. <http://www.bhphotovideo.com/c/buy/Cameras/N/0/Ntt/CA3004LISEF>

precision parts - custom adapters - look into

create a table - FOV vs resolution @ fixed object distance

perspective of establishing ground truth - smaller FOV might be okay - generalize to using color wheel also

color wheel - finger lakes instrumentation flic.com

Sensor Specs
http://www.flicamera.com/spec_sheets/ML50100.pdf

Rodagon Lens system
http://www.rodenstock-photo.com/Archiv/e_Rodenstock_Printing_CCD_43-62__8230.pdf

Appendix 3: Camera Specifications

MicroLine ML50100

PRELIMINARY

Quality. Cooled. Cameras.

8176 x 6132 Imaging Array

6 µm Pixel Size

The new microlensed KAF-50100 is the result of a year-long collaborative effort between ON Semiconductor (and Finger Lakes Instrumentation. Our goal: to create a sensor with both extremely high resolution and excellent quantum efficiency (QE). The significantly boosted QE of the new KAF-50100 sensor brings it in line with popular full frame sensors such as the KAF-16803 and KAF-8300 but with much higher spatial resolution.

At 5" diameter in the front and less than 5" front to back, the ML50100 is a small camera with big camera capabilities. Each component of the camera is designed and manufactured for a long life in the most demanding conditions. The MicroLine ML50100 can cool to 45C below ambient in less than five minutes. Simply set the MicroLine cooling where you want it and the camera will do the rest, quickly and without worries.

Applications

Astronomy
Bioluminescence
Chemiluminescence
Satellite Imaging
Low Light Level Imaging

Features	Benefits
2 channels at 8 MHz each	Fast image capture with full 16-bit resolution
8176 x 6132 Array with 6 µm pixels	Resolves fine detail
Flexible binning and readout	Increases frame rate
Thermoelectric Cooling to 45°C Below Ambient	Excellent low-noise imaging
Excellent quantum efficiency	High sensitivity for fast image acquisition
Optional Nikon F-mount & Canon EOS mount	Wide variety of optical choices
Acquisition software included	Ease of integration with open source SDK
USB 2.0 interface	Industry standard connectivity; fast data transfer

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MicroLine ML50100

PRELIMINARY

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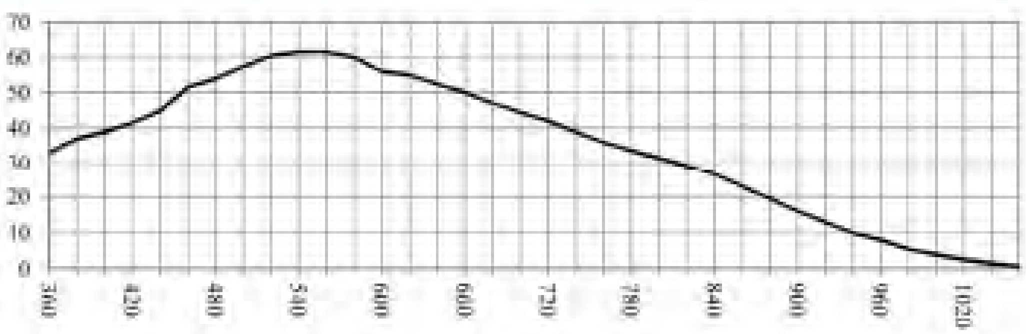
Sensor Specifications (from manufacturer)

Sensor	On Semi KAF-50100				
Pixels	8176 x 6132	**Sensor Size**	49 X 36.7 mm	**Megapixels**	50
Pixel Size	6 µm	**Sensor Diagonal**	61.2 mm	**Video Size (inch)**	3.8
Full Well Capacity	40300 electrons	**CCD Variants**			
Color Options	Mono	**CCD Grades**	Standard		
CCD Type	Full frame	**Anti-Blooming**	800x		

Sensor Quantum Efficiency (Absolute)



Camera Performance

Typical Maximum Cooling	45°C below ambient	**Dark Current (typical)**	.002 electrons/pixel/sec at -25°C		
Temperature Stability	0.1°C	**Cooling Method**	Air (Optional liquid)		
Digitization Speed	Two channels at 8 MHz each				
Typical System Noise	11.5 e- @ 8 MHz			**Non-Linearity**	<1%
Housing Dimensions	6.2 X 6.2 X 3.8 inches (15.7 X 15.7 X 9.6 cm)			**Weight**	4.27 lbs (1.9 kg)
Focal Plane to Face Plate	0.83" optical (21mm)				
Lens Mounts	Optional Nikon F-mount & Canon EOS mount				
Interface	USB 2.0	**Camera Channels**	2		
Available Shutters	65mm				
External Triggering	Standard				
Environment	-30°C to 45°C | 10% - 90% Relative Humidity				
Power	12V (100-240V AC to 12V DC power supply included). With TEC off: <1A. TEC at 100%: 4.6A. Shutter open: 4A pulse for 100msec. Shutter held open, add 0.22A.				

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Lima NY 14485 USA
585 624 3760
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