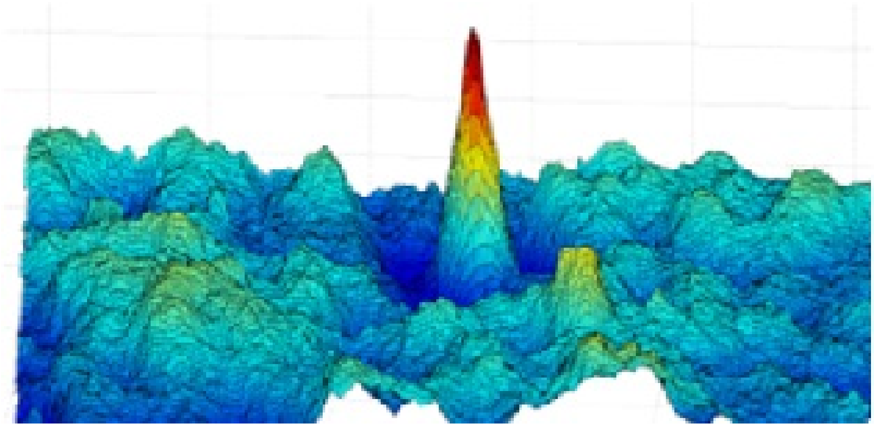
MASTER THESIS

HALMSTAD UNIVERSITY

Master's Programme in Microelectronics and Photonics, 60 credits



New waviness measurement system using RGB LED lights

Panagiota Biba

Master Thesis, 15credits

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New waviness measurement system using RGB LED lights

Improved WMS system using new RGB COB LED lights and a DMX-USB interface – Improved LabView and Matlab for image acquisition and evaluation.

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Abstract

Due to the rapid technological developments in the car industry and the high quality demands of customers, manufacturers and researchers focus on the reduction of surface roughness making use of various surface topography measurement systems.

This master thesis focuses on development of a waviness measurement system (WMS) at Volvo Cars where light from different heights and angles illuminates the surface of an extended object in order to acquire images with different intensities due to shadowing effect and reflection. With this, surface irregularities and imperfections can be detected both in polished and unpolished surfaces for improving the car panels in the manufacturing process.

The initial WMS idea was to illuminate the surface at different heights from the four corners of a dark room using 20 flash lights and a camera positioned exactly on the top of the surface in the middle of the room. The first light goes on and the image is acquired. This procedure continues for all flash lights in 19s.The acquired images were evaluated by Matlab application. With the new WMS system flash lights are replaced by 32 RGB COB LED lights using the DMX512 protocol to communicate with them. The system runs in 9s which is half the time of the old WMS system. New LabView and Matlab codes were adjusted to the new parameters and devices. In the end, measurements were taken with different surfaces, exposure times and color lights. Details of the new devices and software are analyzed in this thesis.

Content

List of Abbreviations

3D / 2D……………..3-Dimensional/2-Dimensional space

WMS...Waviness Measurement System

RGB…………………………………………………………………..Red-Green-Blue

COB……………………………………………………………...Chips on Board

AFM…………………………………………………………Atomic Force Microscopy

DOI…………………………………………………………..Distinctness of Image

BSDF………………………………………Bidirectional Scattering Distribution Function

DMX…………………………………………………………...Digital Multiplex

NI……………………………………………………………..National Instruments

I/O……………………………………………………………………Input /Output

AD……………………………………………………………...Analogue to Digital

ES……………………………………………………………………Energy Sensor

BNC……………………………………………..…Bayonet Neill– Concelman Connector

MAB……………………………………………………………...Mark After Break

SC…………………………………………………………………..Start Code

MTBF…………………………………………………Mark Time Between Frames

CD……………………………………………………………………Channel Data

MTBP……………………………………………………...Mark Time Between Packets

SMA………………………………………………….............SubMiniature version A

NI MAX……………………..National Instruments Measurement & Automation Explorer

LSB……………………………………………………………..Lest Significant Bit

MSB……………………………………………………………...Most Significant Bit

API………………………………………………Application Programming Interface

PTP……………………………………………………………………Peak to Peak

RMS……………………………………………………………..Root Mean Square

List of symbols

Symbol	Description/Meaning	Unit
Eθ	Illuminance	W/m^2
E	Radiant Intensity	W/sr
Θ	Incident angle of light respective to normal of surface	Rad
BC	Distance between the table level to the Led	M
A	Angle	Rad
B	Angle	Rad
C	Angle between	Rad
β	Angle from a pixel to the respective lamp	Rad
α	Angle/slope of the surface	Rad
γ	Angle from a pixel to the four corners	Rad
I_{camera}		W/sr
$f_{scattering}$	Scattering function for the current surface element	
Φ	Angle between observer (camera) and normal of surface	Rad
I_{lamp}	Radiant intensity of the flash lamp	W/sr
Const1	Constant for the current surface element	-
I_{norm}	Normalized Radiant Intensity	W/sr
C2	Radiant intensity if b=0	W/sr
a_x	Slope in the x direction	-
a_y	Slope in the y direction	-
m	Module number(1..4)	-
γ_m	Directional angles in respect to the module m	Rad
a_m	Slopes of the pixel in the direction γ_m	Rad
z	z height	M
xp, yp	Pixel coordinates	M

Chapter 1

1.1 Introduction

Nowadays, the international car industries are becoming more competitive due to the customers' demands for better quality products. With this in mind one of the biggest car industries around the world, Volvo car industry works to meet people's demands for more efficient and better looking cars. Accordingly, researchers make use of surface metrology and topography instruments to scan the cars surfaces in order to detect surface roughness and imperfections. Optical instruments have previously been used to observe surfaces e.g. Profilometers and Interferometers. Our new Volvo's car surface roughness project takes this system one step ahead with the waviness measurement system named WMS, scanning surfaces in three dimensions. Practically WMS uses the wave theory by illuminating a surface from different inclinations and directions in order to acquire the imperfections.

Taking this project one step ahead, Halmstad University proposed that white flash lights be replaced by RGB COB LED light panels in order to improve the old WMS system. This will be analyzed and discussed in detail in the report below along with the fundamental laws of physics, software used and data acquisition to support the upgraded WMS project.

1.2 History of measuring surface roughness

Different methods for measuring surface roughness of surfaces have been developed for a long time in industry. Schmalz[1] developed the first stylus instrument and presented the evaluation parameters of a basic line in 1929. The first commercially available instrument for measuring surface roughness was made by Abbott in 1936. The instrument can produce output from the mechanical probe to an electrical signal so that substantial magnifications could be achieved. Talysurf that used a stylus to measure surface roughness was made in Britain in 1940. Since then, many countries have developed many types of instruments: microscopes for measuring surface roughness were made in Germany and Russia in 1951 and 1958.

In recent years, Scanning Electron Microscope, Laser Interferometers and Atomic Force Microscope (AFM) technologies have also been used for measuring surface roughness with extremely high precision. Methods for measuring surface quality generally can be divided into two categories: contact and noncontact measurements. For contact measurement, a stylus is used to touch the surface to be measured. Signals can be transferred from mechanical to electrical while the stylus is moved. In this way, the surface profiles can be attained. For noncontact measurements, optical microscope, electron microscope, or optical sensors are used to measure and collect surface parameters. The noncontact techniques are usually optical, using either a regular light source or laser. The optical methods can measure Gloss, DOI (Distinctness of Image) and Orange Peel. Gloss is a measure of how well light is reflected from the surface without scattering. DOI is a measure of the mirror-like qualities of the surface, and Orange Peel is a measure of the roughness or waviness of the surface. Noncontact systems can measure soft surface area and large surface area more easily than contact systems. However, noncontact systems tend to be more expensive than contact systems. Also noncontact systems may be affected by the material color or some other optical properties of the surface. High accuracy and resolution can be achieved by both noncontact and contact measurement systems [2]

1.3 Background Car Industry Knowledge

Car panels are very important parts since they are directly visible to the customer. The impression of a car is determined by an appealing design of its body, the color and gloss of its paint, and the manufacturing and assembly accuracy of the exterior body panels.

If the panel has surface defects which are not allowed in a quality standard, the dye should be modified. The circle of the panel inspection and dye modification would be up to one month. Defect inspection and quality evaluation of the panel is still processed manually.

In the automotive industry, high gloss is usually obtained on the painted panels. The high gloss makes the surface appearance sensitive to waviness in the painted surface. This waviness in the surface is, when focusing on the paint surface, observed as a wavy light/dark structure often referred to as orange peel. This light/dark structure is formed by the fact that the painted surface structure contains different slopes which influence the amount of reflected light.

Figure 1.1: Car panel defects.

One of the most common defects is a ‘hollow’ which is identified when the surface is painted because the glossy top-layer in a painted system makes the panel surface reflective. When painted, the hollow creates an optical distortion because the geometry of the defect leads to varying focal lengths in the reflections from a panel. A hollow can have widths that are between 30mm and 60mm wide. [3]

The defects can appear as depressions, elevations, bimps, orange peel-like and local thinning.

1.4 Fundamental Theory and Laws

When light hits a surface, it can be either reflected away from the surface or refracted through the surface to the material beneath. Once in the material, the light can be transmitted, absorbed, or diffused (or some combination) by the material.

1.4.1 Reflection

There are three general types of reflection: specular, spread, and diffuse, as shown in Figure 1.2. A specular reflection, such as what you see in a mirror or a polished surface, occurs when light is reflected away from the surface at the same angle as the incoming light's angle. A spread reflection occurs when an uneven surface reflects light at more than one angle, but the reflected angles are all more or less the same as the incident angle. A diffuse reflection, sometimes called Lambertian scattering or diffusion, occurs when a rough or matte surface reflects the light at many different angles.

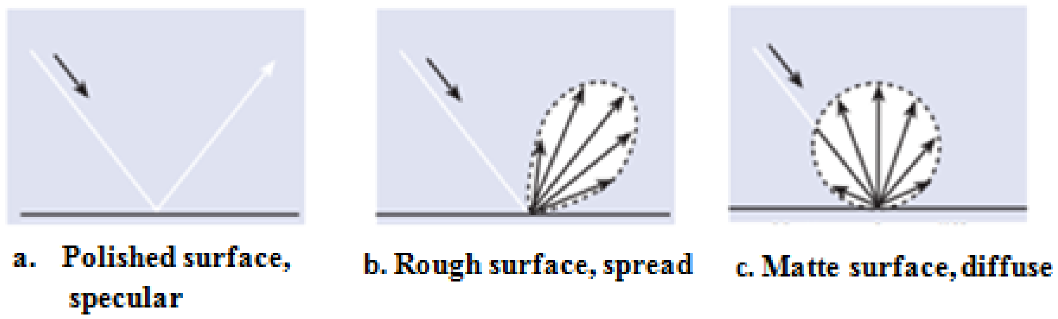


Figure 1.2: Specular, spread and diffuse reflections from a surface.

1.4.2 Diffusion (Scattering)

When light strikes a perfectly smooth surface, the reflection is specular, as explained in the previous section, "Reflection." When light strikes a rough surface, the light is reflected or transmitted in many different directions at once, which is called diffusion or scattering.

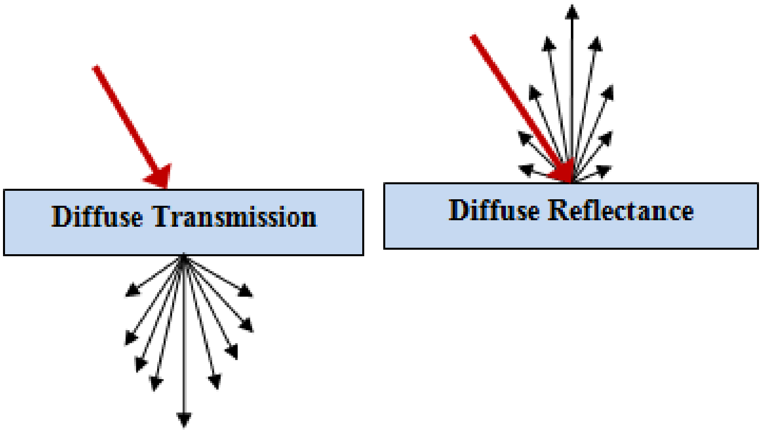


Figure 1.3: Diffuse transmission and reflectance.

The amount of diffuse transmission or reflection that occurs when light moves through one material to strike another material depends on two factors:

- The difference in refractive index between the two materials
- The size and shape of the particles in the diffusing material compared to the wavelength of the light. For example, the molecules in air happen to be the right size to scatter light with shorter wavelengths, giving us the color of blue sky.

One method of describing diffusion is the bidirectional scatter distribution function (BSDF), which quantifies scatter and its effects.

1.4.3 Lambert's Cosine Law

Lambert's cosine law states that the illuminance falling on any surface depends on the cosine of the light's angle of incidence, θ. Remember from the previous, "Reflection," that the angle of incidence is measured from a line normal to the surface.

$$\boxed{E\theta = E\cos\theta \qquad (1.1)}$$

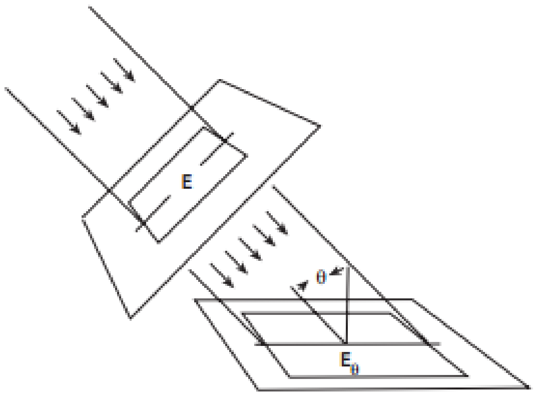


Figure 1.4: Lambert's cosine Law.

1.4.4 Lambertian Emission and Reflection

A Lambertian surface reflects or emits equal (isotropic) luminance in every direction. For example, an evenly illuminated diffuse flat surface such as a piece of paper is approximately lambertian, because the reflected light is the same in every direction from which you can see the surface of the paper. However, it does not have isotropic intensity, because the intensity varies according to the cosine law.

Figure 1.5 shows a Lambertian reflection from a surface. Notice that the reflection intensity follows the cosine law. Remember the luminance is intensity per unit area. Because both intensity and apparent area follow the cosine law, they remain in proportion to each other as the viewing angle changes. [4]

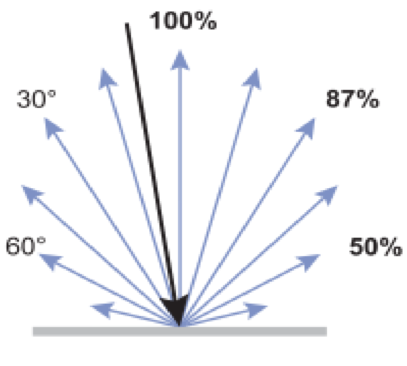


Figure 1.5: Lambertian surface.

1.5 How do we see roughness?

1.5.1 Observing light scattered by the surface

The easiest way to see what is on a surface is to view it under bright, uniform illumination. By turning the surface in various directions, large scratches having different orientations can easily be seen. Although smaller scratches, particulates, micro irregularities and matching marks can only be observed under microscope, it is possible to infer the presence of certain types of defects by the scattering they produce. Dust particles and some types of scratches scatter mainly close to the direction of secular reflection. Isolated scattering centers will appear as bright specks on the surface. It is best to observe samples on a clean bench or in a clean room, because otherwise dust can fall on a sample while it is being inspected. [5]

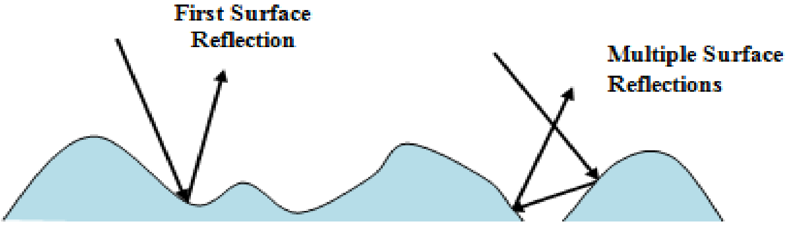


Figure 1.6: Reflection processes at surfaces.

1.5.2 Shadowing and masking

The effect of self-shadowing and self-masking by a rough surface (Figure 1.7) was introduced in computer graphics by Blinn and Cook. This effect manifests itself at large angles of incidence or reflection, where parts of the surface are shadowed and/or masked by other parts, reducing the amount of reflection. [6]

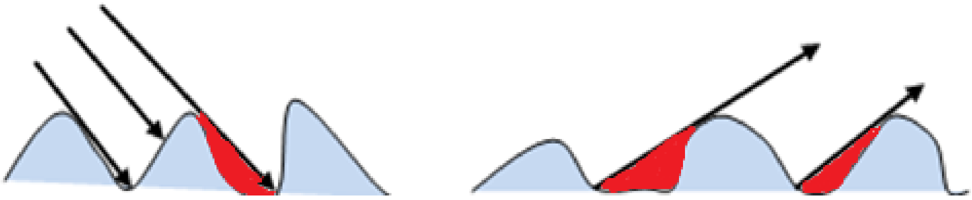


Figure 1.7: Shadowing and masking.

Chapter 2

2.1 Old WMS system with flash lights - Description

The main idea behind WMS is the dependence of the illuminated surface on the position and orientation of the observer (light source).In the previous project flash lights where positioned one on the top of the other in each of the four corners. The dimension of the dark room is approximately 3.0 x 3.0 x 2.2 meters, which was later enveloped in black cloth to reduce outside lightning and reflections. In each of the four corners, a vertically arranged module (1 to 4) is found consisting of 5 flash lamps and an energy sensor (photosensitive sensor), which measures the radiant intensity of opposite flashes. A camera is positioned on top in the middle of the system, nearly a meter above the measurement table.

The previous WMS system with flash lights was using LabView from National Instruments for data acquisition and hardware control and Matlab from Math Works for image processing.

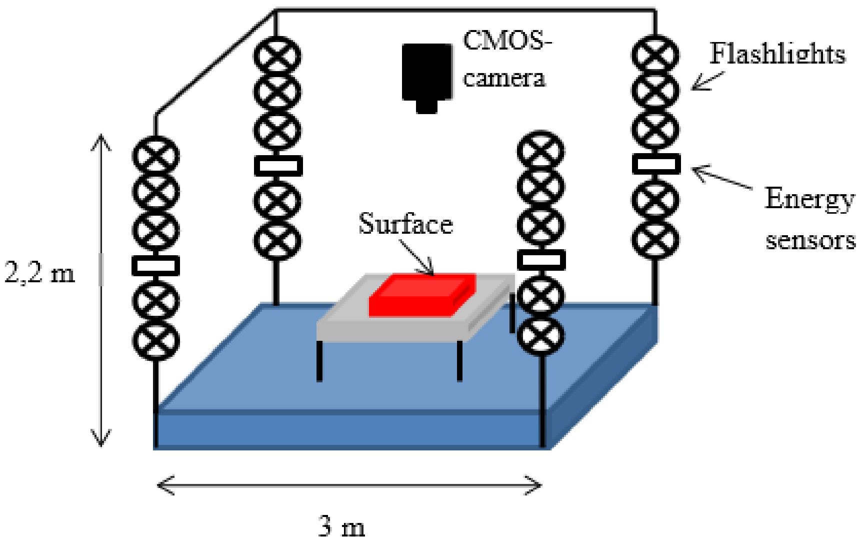


Figure 2.1: The basic layout of the WMS illumination of the sample by five flashlights. In every corner is a sensor which measures the illumination intensity of the opposite flash lamps.

On each module, five flash lamps and one energy sensor are connected in parallel. The numbers of the energy sensors are equal to the ones of the modules. The flashes are numerated from one to five, where one is the lowest and five the highest mounted flash box.

By using light sources in opposite directions, the errors are relatively low, since they are nearly equal and thus cancelled due to the images' differences.

2.2 Layout - Devices

Here we can see the connectivity (general rooting) of the flash lights for the WMS system:

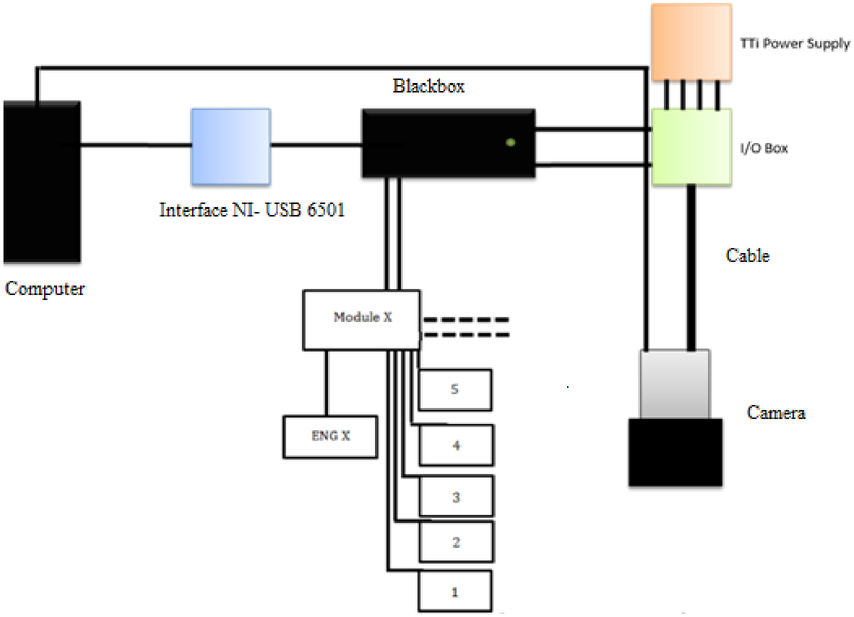


Figure 2.2: Connectivity (wiring) of flash lights with the system.

As we can see from the wiring between the computer and the Blackbox an NI interface box was connected. The Blackbox was connected both to the I/O Box (which in turn was connected with the power supplier) and to the flash lights. Each module was serially connected including an energy sensor. Moreover, the camera was connected to the I/O Box and computer for image acquisition. Clearly, the wiring for the old system was troublesome so a new more simple system was important to develop.

2.2.1 The Blackbox.

The Blackbox is the connection between the National Instruments interface and the WMS bus system. Its main functions are to set the single modules/flashes, synchronize the flashlights with the camera, serve as the WMS-bus power connection and read the energy sensors. To be able to accomplish all the previously mentioned tasks, it has several connectors. Last but not least, the above functions are determined by the Blackbox hardware design and cannot be changed.

Figure 2.3: Blackbox backside.

2.2.2 Energy sensors

In the WMS system, the energy sensors are needed and used for normalizing the different intensity levels that are radiated by the various flash lamps. A sensor box contains a photo diode, which has a diffusor in front of the entrance window, and a capacitor. After every single picture, the raw analog energy level is read by the respective module, AD converted in this module box and sent to the Blackbox as two 8-bit numbers. Each element in the system (module, flash or energy sensor) has its own address and has to be set and reset for every single acquisition. Before a new image could be taken, the energy level memory of the modules has to be reset.

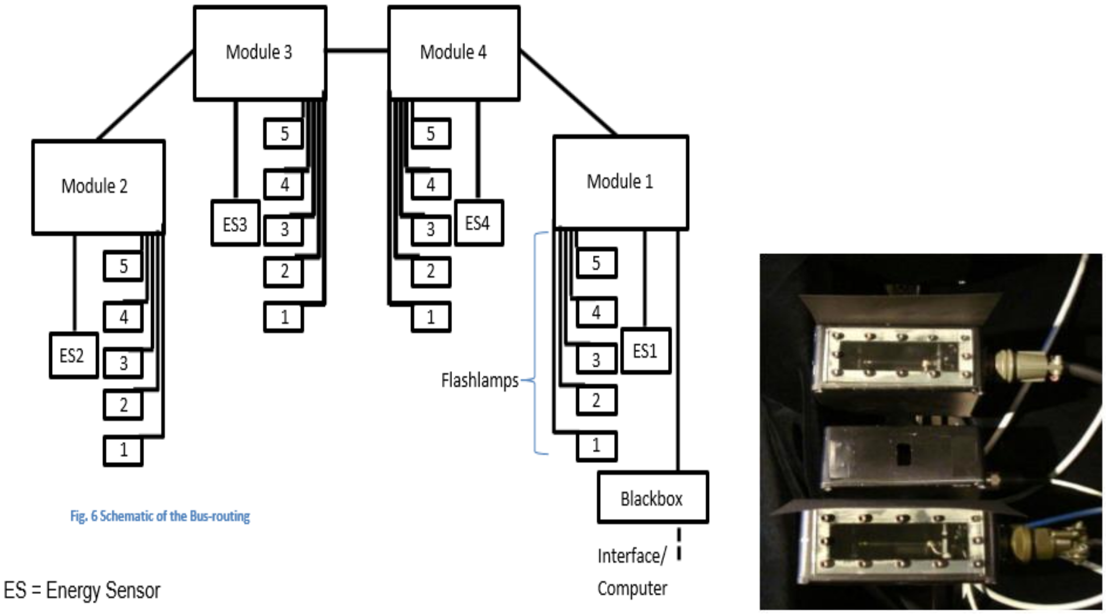


Figure 2.4: Energy sensor between two flashlights.

2.2.3 Camera

For the image acquisition itself, a Basler GigE acA2040-25gm is now used. It's a grayscale camera with a resolution of 2048x2048 pixels and can store a number of ne = 13500 electrons in each pixel (full-well capacity). The connectors comprise one Ethernet cable for the image/command data exchange and one Basler 6 pin I/O HRS socket for the power supply, the frame start trigger and the exposure time signal. The features like gain, exposure time and how the camera should behave can be set as default via the National Instruments Measurement Automation Explorer or with a node in LabVIEW.

Figure 2.5: A Basler GigE acA2040-25gm used in the WMS system.

The range of the focus from the front of the lens varies between 0.35m and infinity. With this camera lens, the measuring area was around 40 cm x 40 cm and the pixel size around 200 µm x 200 µm at the table level. To get a bigger or smaller measuring area/pixel size, another lens has to be mounted. (Smaller measuring area = smaller pixel size = ability to measure finer structures and defects).

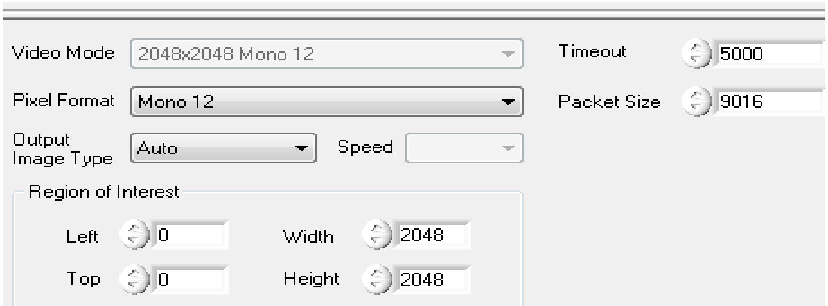


Figure 2.6: General Camera Hardware Settings in NI MAX.

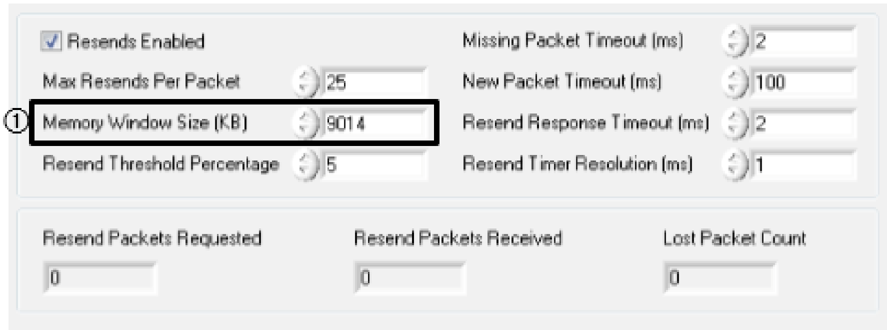


Figure 2.7: Transfer Camera hardware Settings.

Figures 2.8 and 2.9 show the quantum efficiency (the number of electrons released by a photocell per photon of incident radiation of a given energy) of the camera according to wavelength and the RBG spectrum, respectively.

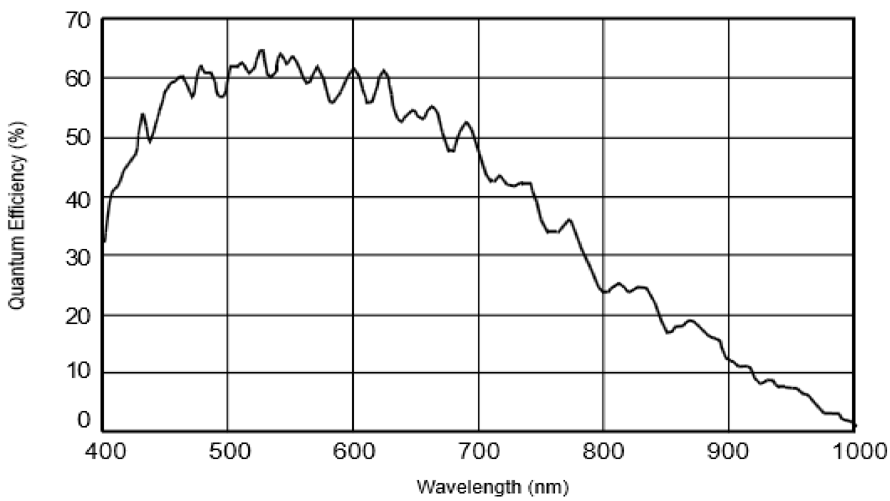


Figure 2.8: Spectral response of the quantum efficiency for acA2000-50gm

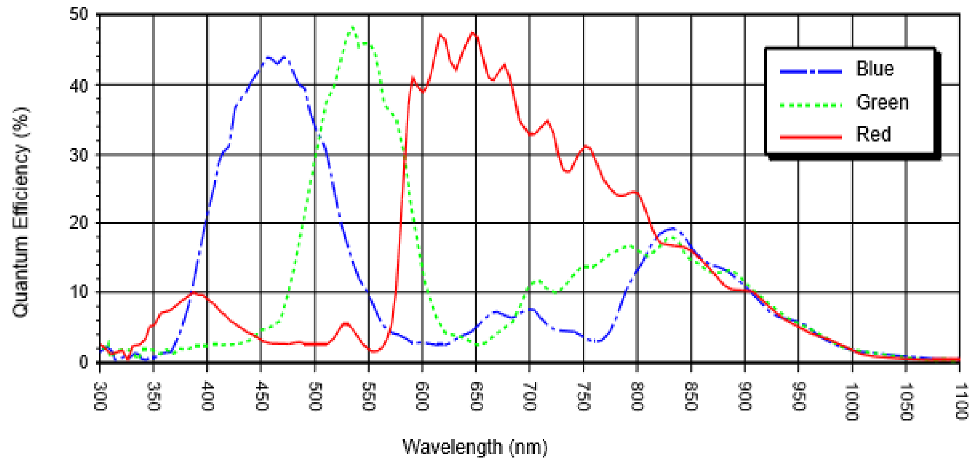


Figure 2.9: Quantum Efficiency for RGB colors.

2.2.4 I/O Box and I/O Box Power Supply

The I/O Box was needed to have a lucid routing for the signals that are going in and out of the camera. Also it was used to wire the power supply with the I/O cable and to convert the exposure time signal to a useable 5 V signal. As I/O Box power supply, a Device named QL255TP from TTi was used.

<u>Connectors of the I/O Box</u>

- 4x laboratory plug for the power supply input and 5V conversion.
- 2xBNC socket for camera in-an output signals.
- 1x6 pin digital HRS cable for power supply of the camera and I/O signals.

Figure 2.10: Picture of the I/O Box and on the left side and picture of the I/O Box Power supply on the right side.

2.2.5 NI Interface

In the previous WMS project, the NI- USB 6501 interface was used to interface Labview with the Blackbox.

Figure 2.11: NI Interface.

2.3 Anti-Reflection System

Because of some reflections caused by the black painted metal camera mounting, it was necessary to cover these parts and we did this by using an antireflection shield. Two cardboard cones, one inside another. The inner cone has to be as big as the field of view of the camera, the outer one on the broadest position the size of the table. Both have to end on the same height.

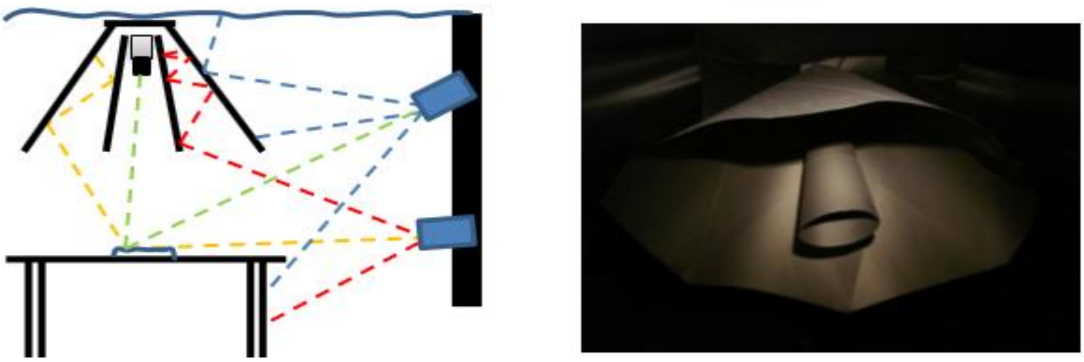


Figure 2.12: (Left side picture)Antireflection Shield schematic.(Right side picture)Anti Reflection Shiled.

Chapter 3

3.1 New WMS system using 4 LED RGB panels-Description

The previous WMS flash lights system set the basis for measuring the surface irregularities in the car panels. The goal of this thesis project is to develop an upgraded version of the system with better performance. For this reason the new upgraded WMS system is now faster and more efficient. The first disadvantage was to get rid of the Blackbox which made the communication between the computer and the flash lights difficult. For this reason the Blackbox was replaced by a USB DMX interface bus which is commonly used in theatrical and musical performances. The programming of the lights is very easy and gives us many possibilities. Moreover, the flash lights were replaced by 4 RGB COB light panels with 8LED lamps in each module. In this case, we can use coloured light and the intensity of each lamp is fixed and stable compared to the flash lights in which the intensity was always adjusted.

With the above changes in mind, a new LabView programme was made in order to programme the lighting and to control the camera acquiring the images. The Matlab Evaluation application was adjusted to the new parameters as well. Changes of LabView and Matlab are presented in detail in the next Chapter.

3.2 The set up - Hardware

In the new upgraded WMS system the 4 RGB COB LED panels were placed in the four corners of the dark room in positions which were calculated to illuminate the surface from the best angle as presented below. In the flow chart below we can see how the system works. The four panels were serially connected which means that the output of the first panel is connected with the input of the second one and so on. Panel number 1 is connected with the USB controller and this in turn is connected to the computer.

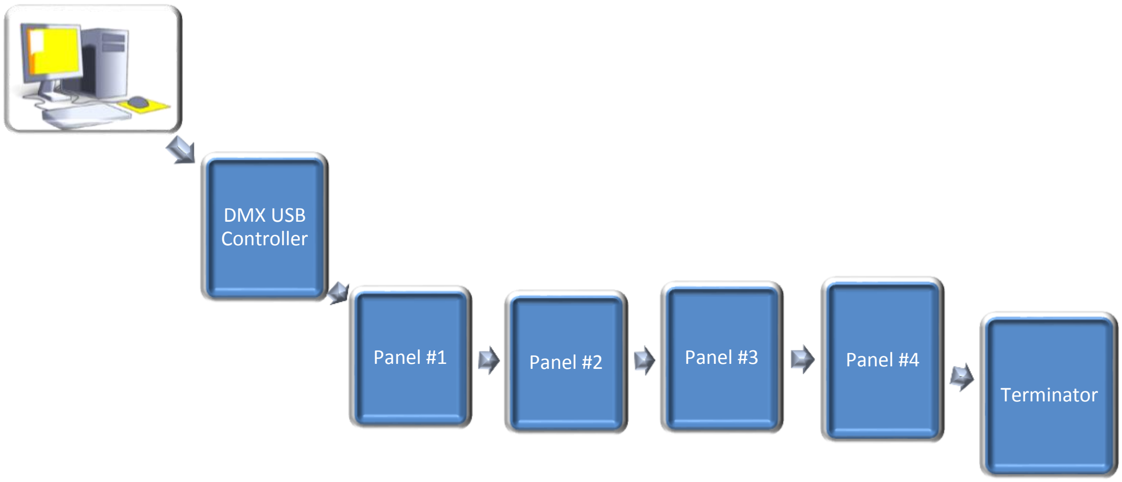


Figure 3.1: The connection devices in the new WMS system

In the following we describe the devices used.

3.2.1 LED PMB-8 COB RGB 30W Bar from Eurolite.

Figure 3.2: Picture of the new RBG-COB LED panel

<u>Important features</u>

- Equipped with 8 x 30 W COB LEDs in the colors red, green and blue
- 3, 5, 24 or 27 DMX channels selectable for numerous applications
- Each LED can be controlled individually
- Functions: Static colors, RGB color blend, internal programs, dimmer and strobe settings via DMX, Master/Slave
- DMX-controlled operation or stand-alone operation with Master/Slave function
- Comfortable addressing and setting via control panel with LCD display and four operating buttons
- After every 8 devices the fixtures must have a renewed connection with the power mains
- DMX control via every standard DMX controller

Power Supply	230V AC, 50Hz
Power consumption	240W/370 VA
DMX control channels	3/5/24/27
DMX512 connection	3-pin XLR/5-pin XLR
Flash-rate	18Hz
Sound-control	Via built-in microphone
LED type	Cluster 30W, RGB
Beam angle	Approx. 60^0
Dimensions(Lx W x H):	150x880x165 mm

Table 3.1: Technical Specifications for the LED PMB-8 COB RGB 30W Bar.

3.2.2 DMX USB PRO from ENNTEC

Figure 3.3: DMX USB interface box

The DMX USB Pro is an industry standard interface for connecting PCs and MACs to DMX512 lighting networks.

Features:

- Control up to 512 channels(software permitting)
- LED indicator to show proper function.
- Includes USB cable and driver CD

Power Requirements	300m A supplied by USB
Refresh rate configurable	1 to 40Hz with a full 512channel frame

Table 3.2: Technical specifications for the DMX USB Pro box

3.2.3 Camera AcA2040-25gm/gc

As already said in Chapter 2 a Basler GigE acA2040-25gm camera was used for image acquisition (see details in Chapter 2). It is a grayscale camera with a resolution of 2048x2048 pixels.

- Minimum allowed exposure time: 24µs
- Maximum possible exposure time: 1s

3.3 Software used

3.3.1 DMX Protocol

DMX is an acronym for Digital Multiplex, a communication protocol used to remotely control lighting dimmers and intelligent fixtures. It is designed to provide a common communications standard between these lighting devices regardless of the manufacturer.

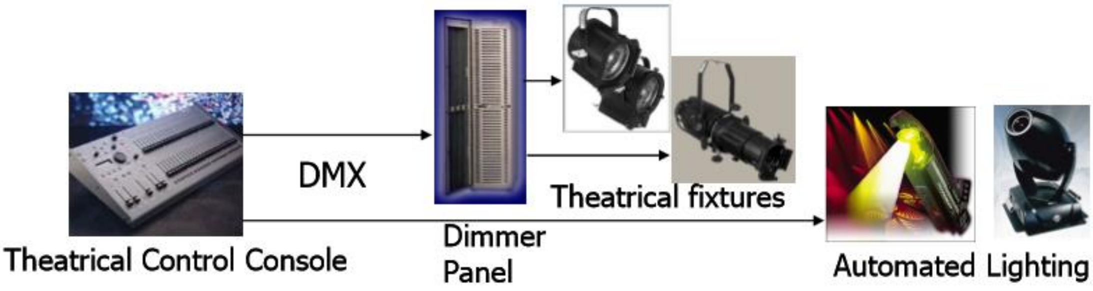


Figure 3.4: Examples of DMX interface connections/applications.

The DMX 512 signal is a set of 512 separate intensity levels (channels) that are constantly being updated and each level has 256 steps divided over a range of 0 to 100 percent. The DMX signal repeats all 512 intensities as fast as 44 times per second

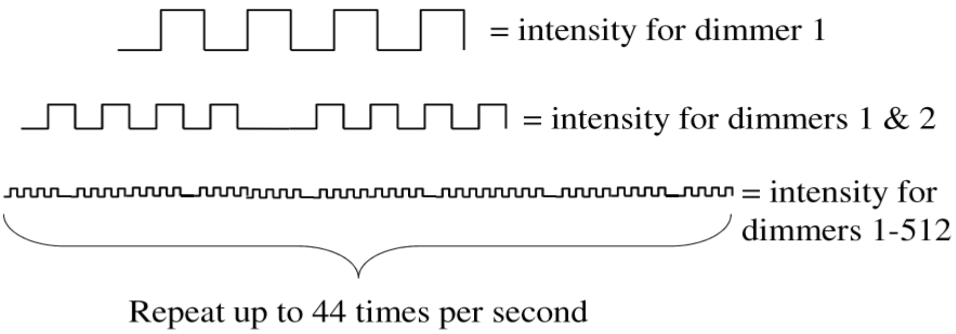


Figure 3.5: DMX signal representation

The DMX 512 protocol, commonly known as Recommended Standard 485 or RS-485, uses asynchronous, differential data transmission. This standard supports 32 devices on one network at a distance of up to 4000 feet. One device functions as the master (the DMX controller) in a network, while the rest function as slaves (dimmers, intelligent fixtures, etc.). Only the master transmits over the network, and all slaves receive the same data.

In asynchronous data transmission, data are sent one byte at a time. Asynchronous devices do not require perfect synchronization, but their timing signals must be close (within about 5%). This method is relatively simple, and therefore inexpensive.

Differential data transmission offers superior performance in most applications by helping to nullify the effects of interference on the signal. This is achieved by using two wires to transmit the signal (with opposing polarity) instead of just one.

Devices are connected in a daisy-chain fashion, from the controller to device #1, then device #1 to device #2, and so on. The final device in the daisy-chain must be terminated. The terminator absorbs signal power which would otherwise be reflected back into the cable and degrade the data. A terminator simply places a 110-120 Ohm, 0.5 Watt resistor across the two transmission wires.

DMX transmission:

DMX 512 data are transmitted at 250 kHz, meaning that 250,000 1's and 0's (at a maximum) can be sent each second. Each bit is measured in 4 microsecond (µs) intervals. In order for the receiving device to correctly interpret the data, it must be sent in a particular sequence. A single transmission (DMX Packet) includes synchronizing elements and channel data for up to 512 channels

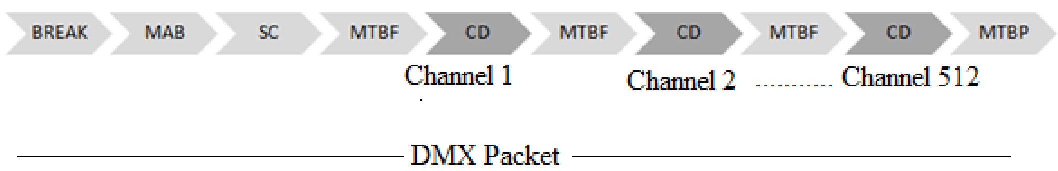


Figure 3.6: DMX Packet transmission

Element	Description	State	Size	Duration
Break	The Break resets the line, signaling a new DMX packet	LO(0)	22-250kbits	88µs-1sec
Mark After Break(**MAB**)	The MAB signals the receiver to begin reading data	HI(1)	2-250kbits	8µs-1sec
Start Code (**SC**)	The SC is identical in size to channel data, but always 0 in value.	Mixed	11bits	44µs
Mark Time Between Frames(**MTBF**)	The MTBF is used to space out individual data bytes	HI(1)	0-250kbits	Up to1sec
Channel Data (**CD**)	The CD carries the 8-bit DMX value for each channel, plus one start and two stop bits.	Mixed	11bits	44µs
Mark Time Between Packets(**MTBP**)	The MTBP is used to space out entire DMX Packets.	HI(1)	0-250kbits	Up to 1sec

Table 3.3: DMX Packet elements description.

3.3.2 Thorlabs CCS spectrometer

For measuring the wavelength of the light we used a CCS series spectrometer from Thorlabs

Figure 3.7: 1) USB port 2) Fiber input (SMA connector) 3) Status LED 4) Trigger Input (SMB connector)

Wavelength Range	350-700nm
FWHM Spectral Accuracy	<0.5nm @ 435nm
S/N Ratio	≤2000:1
CCD Security	160V/(lx*s)
Integration Time	10μs-60s

Table 3.4: Technical specifications for the CCS spectrometer.

Graphical User Interface : Features

- Operates up to 10 Devices simultaneously
- Available Filters: Peak Finder, Smoothing, Averaging, flip/Revert Picture
- Algorithms: Gaussian Transformation, Absorbance, Transmittance and
- User Selectable Colors and Shapes
- Polynomial or Gaussian Data Fitting

3.3.3 National Instruments Measurement & Automation Explorer (NI-MAX)

National Instruments provides Measurement & Automation Explorer (MAX), a graphical user interface, to configure IVI. MAX is usually installed with one of the NI application development environments such as LabView. With the IVI configuration utility, you can interchange instruments without recompiling your application source code by configuring logical names and driver sessions in MAX. You define which specific instrument to associate with a logical name and IVI takes care of the rest. If at a later time, you decide to swap the instrument and use a different one; all you need to do is change the entry in the configuration utility so the logical name points to a different driver session.

3.3.4 LabView

LabView is a development environment for problem solving, accelerated productivity, and continual innovation. In both flash lamps WMS system and RGB LED panel WMS system we used LabView to automate our project and communicate computer with the devices. The changes in Labview are presented in Chapter 4 in detail.

3.3.5 Matlab

MATLAB is a high-level computer language and interactive environment for numerical computation, visualization, and programming. Using MATLAB, you can analyze data, develop algorithms, and create models and applications. In the WMS system Matlab is analyzing and evaluating the images taken from Labview in order to get the surface profile of the illuminated surface. The new Matlab is adjusted to work for 32LED lights compared to 20flash lights in the old system. Furthermore, LED parameters like x-y-z positions are introduced in the new Matlab application which is presented in the next Chapter in detail.

3.4 Lamp positions

The next step for the new WMS is to calculate the angles of each lamp and the position of the panel, not only to get the parameters that we will insert in Matlab but also in order to mount the panel in the best position so as the surface to be best illuminated.

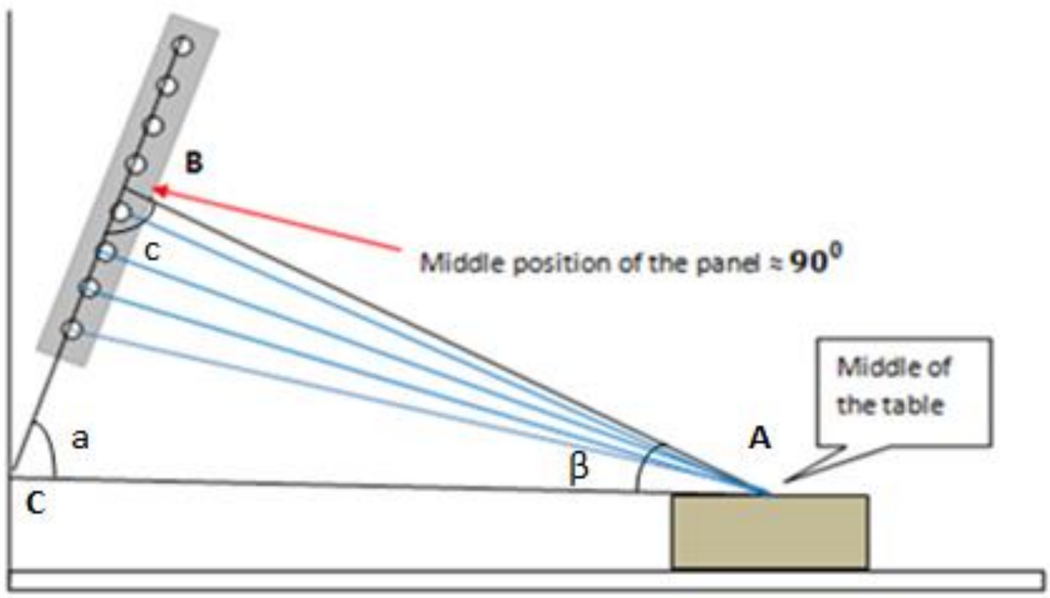


Figure 3.8: Calculating angles between the panel and the illuminated surface (middle of the table)

The middle of the panel which is perpendicular to the illuminated surface gives us the best angle to mount the panel.
Using the cosine law we have:

$$\boxed{C^2 = A^2 + B^2 - A*B*Cos(C) \qquad (3.1)}$$

$C^2 = A^2 + B^2 - A*B*Cos(C)$ => $(2.02)^2 = 0.63^2 + 1.92^2 - 2*0.63*1.93Cos(C)$ =>
$Cos(C) = 0.0123$ => $C = Cos^{-1}(0.0123) = 89.3^0$ so we see that $\mathbf{C \approx 90^0}$

$\alpha = sin^{-1}\left(\frac{1.93}{0.63}\right) = \mathbf{71.9^0}$ βmiddle = 180-(90.3+71.9) = $\mathbf{17.8^0}$

LED		BC (m)	c(^{0})	α(^{0})	β(^{0})
LED1	X=AB =1.93(m)	0.38	88.51	71.9	6.97
LED2		0.27	85.26	71.9	10.14
LED3		0.16	82.03	71.9	13.37
LED4		0.05	78.86	71.9	16.61
LED middle		0.63	$\approx 90^0$	71.9	17.88
LED5		0.05	88.51	77.15	19.38
LED6		0.16	85.26	77.15	22.62
LED7		0.27	82.03	77.15	25.85
LED8		0.38	78.86	77.15	29.02

Table 3.5: Angles of the LED lamps

Example for LED4:

X4=0.05m, AB=1.93m, c1=$tan^{-1}(\frac{1.93}{0.05}) = \mathbf{88.51^0}$

$\beta 1$ = c1-α =88.51-71.9= $\mathbf{16.61^0}$.

3.5 Intensity of lights

3.5.1 Flash lights:

Here is the spectrum of the flash lights (white light) using the spectrometer "CCS100" from Thorlabs.

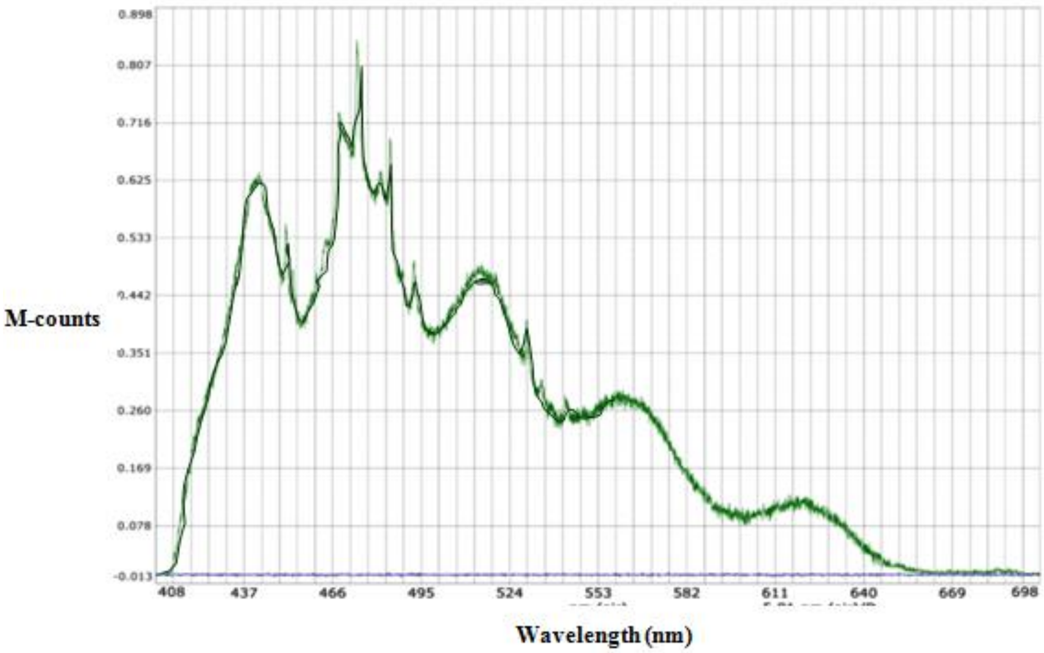


Figure 3.9: Spectral Radiant Intensity of flash lights (white color).

As we can see from Figure 3.9 the spectrum fluctuates starting from 410nm and ends at 650nm. Highest peak is seen at 470nm and next ones at 440nm on the left side and 520nm on the right from the highest peak.

3.5.2 LED lights:

RGB colors for 60ms integration time.

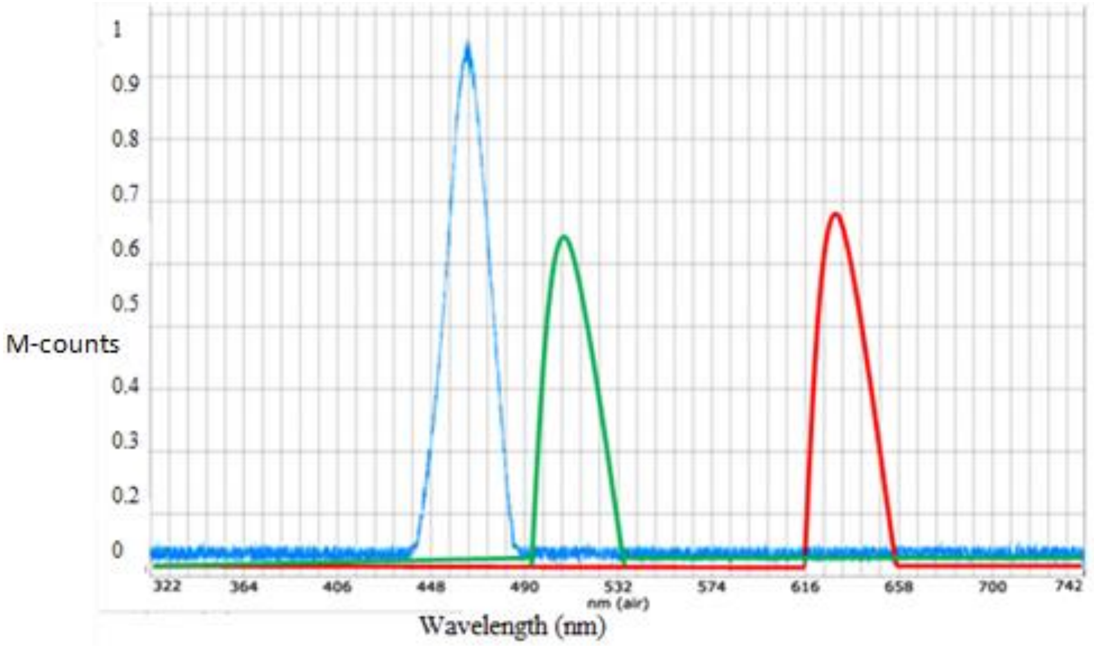


Figure 3.10: Spectral irradiant intensity for Red, Green and Blue (RGB) LEDs with maximum intensity

As seen in the spectrum of the RGB LEDs in Fig.3.10, the M-counts for blue color are higher than for red and even more than for green.

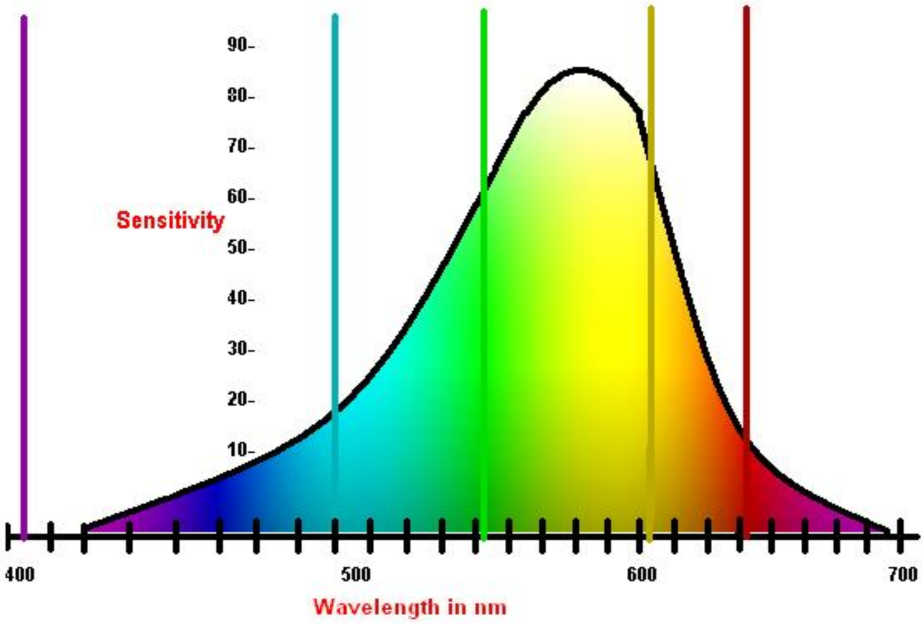


Figure 3.11: Sensitivity of the human eye according to wavelength range (color).

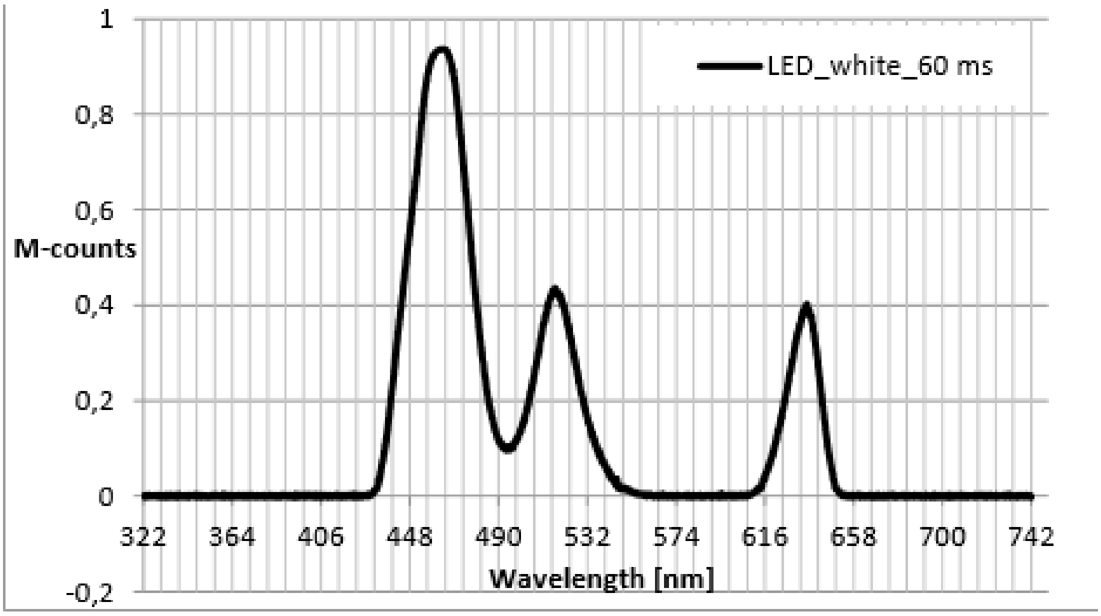


Figure 3.12: Spectral Radiant Intensity of LEDs in white light.

In figure 3.12 we can see the spectral radiant intensity of the white light from the LEDs. Evidently, the mixture of blue, green and red colors for these LEDs will look “bluish” (cold blue-white).

Chapter 4:

4.1 New LabView software

4.1.1 Font Panel and Energy values

In order to control the panel lights from the computer we used Labview (Laboratory Virtual Instrument Engineering Workbench) from National Instruments. Labview provides a graphical programming environment, replaces lines of code with interconnected icons and allows “easy” automated data acquisition, instrument control, and industrial automation. Moreover, Labview programs are called virtual instruments (VIs) and this is because their appearance (like a circuit schematic) and operation imitate actual instruments/circuit blocks.

LabVIEW is in this case used for data acquisition, image acquisition and hardware control. Because of its simplification, the use of IMAQdx (image acquisition box) and the DAQmx (data acquisition box) is particularly important for handling the camera and the interface, why it has to be studied with a special focus.

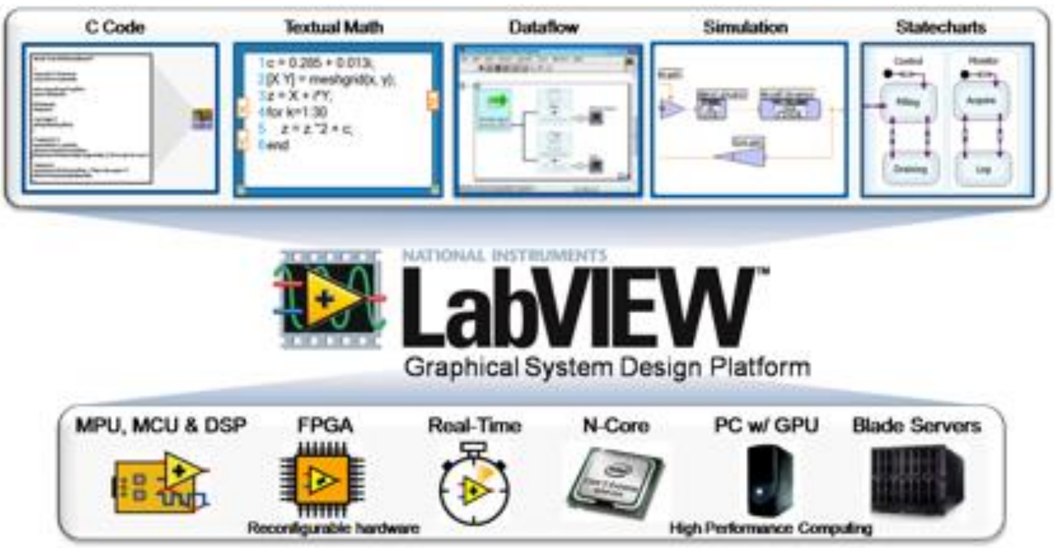


Figure 4.1: Labview, the graphical programming environment

In the new upgraded system we replaced 5 flash lights with the LED RGB Panel lights which are controlled by the USB interface bus. In this case not only did we remove the Blackbox but also we changed the Labview in order to meet our new needs and run with the DMX protocol.

This is the final Labview programme for running the new upgraded system with 32Led lamps using the DMX protocol. In order to understand how the visual programming works we divided the Labview into separate stages.

In detail, we recorded 93 different measurements with different parameters .In total in each measurement we took 32images so in the end we had 2976 different images. The evaluations in Matlab run 93 times.

Here we can see the front panel of the Labview in which we can set/select the parameters before we run the programme.

As seen from the front panel of the Matlab in the Category of ‘Measurement’ the researcher can select the color of the 4 panels (Red, Green, Blue and White), the intensity of the lamps from 0 which indicates no light to 255 with the highest brightness and exposure time which can be manually adjusted. The measurement won’t start if the “Start Measurement” button is not on.

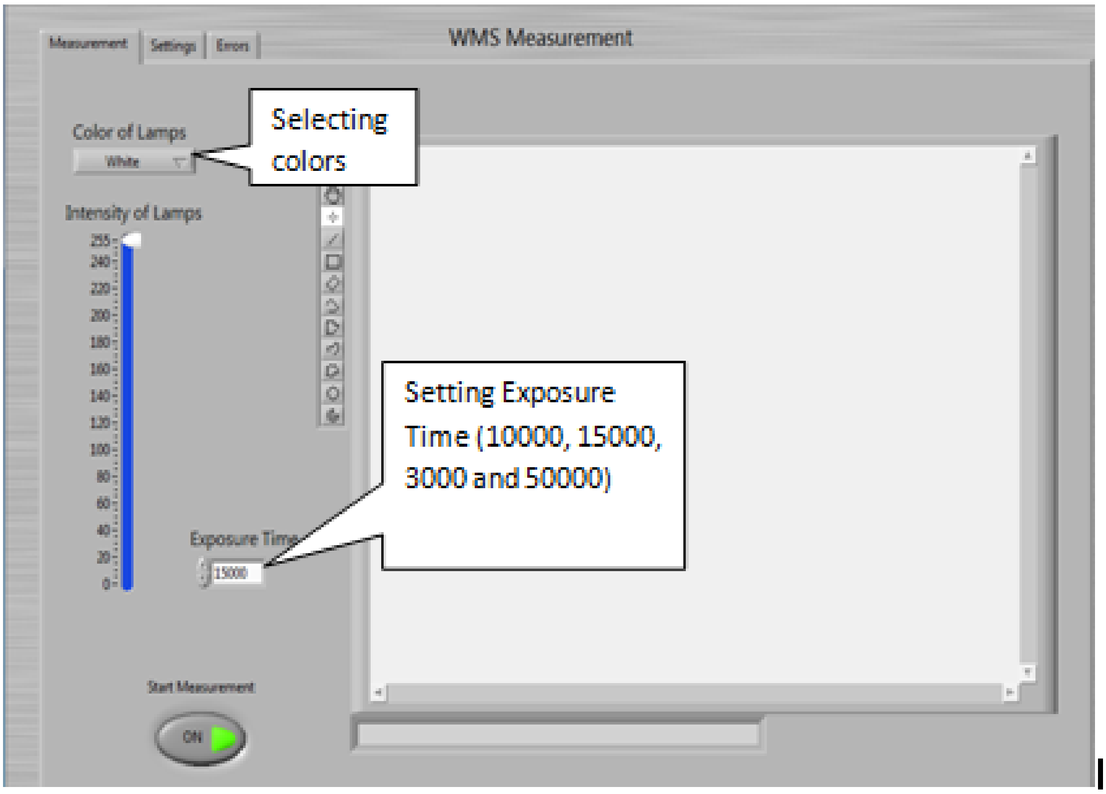


Figure 4.2: Front panel Labview – setting the parameters

On the right side of the front panel during the running of the system the photos are shown on the white “Image” window. We have two more categories in the front panel before we run our Labview; these are “Setting” and “Errors”. In setting we can choose how many lamps we want to use in our system. For example if we choose 20 instead of 32, the first 20 leds are going to be on (from led1_1 to led3_4). On the last category of the front panel we get the errors (see Figure 4.3).

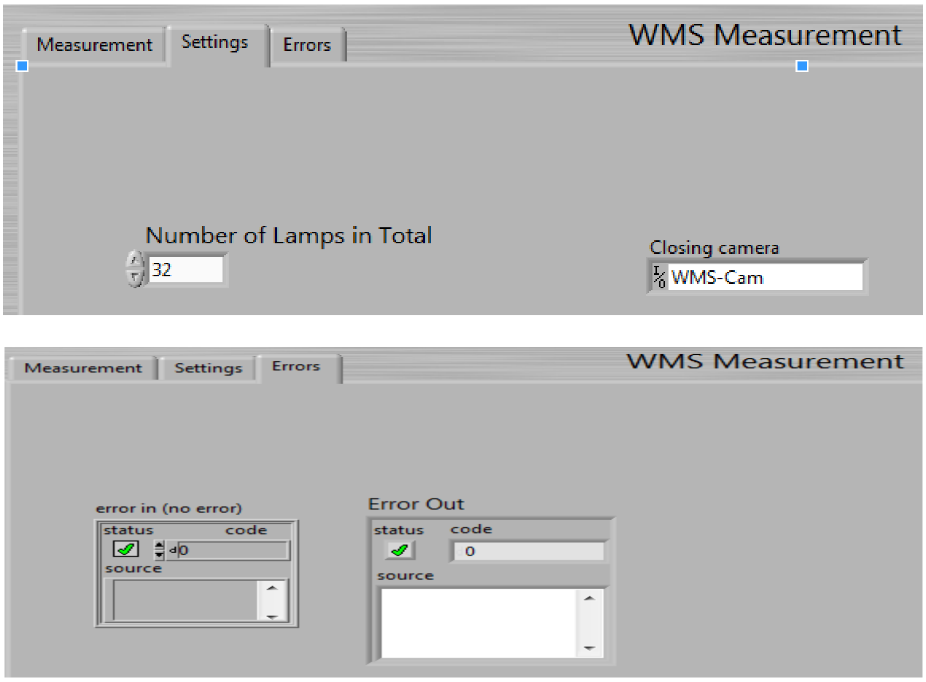


Figure 4.3: WMS Measurement-Front panel 'Settings' and 'Errors'.

Step 1: Setting parameters from Front Panel (Color, Intensity and Exposure time).

Step2: Saving the images in the Matlab/IMAGES folder

After we set the parameters we run the Labview. Images are saved in the selected folder. Is preferable to save the images in the Matlab images folder where the fixed energy values are. The images and energy files should have the same name for the Matlab application to run. For example, the images initial name is "15et" (see Figure 4.4) and is going to be saved from "15et1_1" to "15et4_8" and energy names from "15etEnergy1" to "15etEnergy4". (15et means 15000ms exposure time).

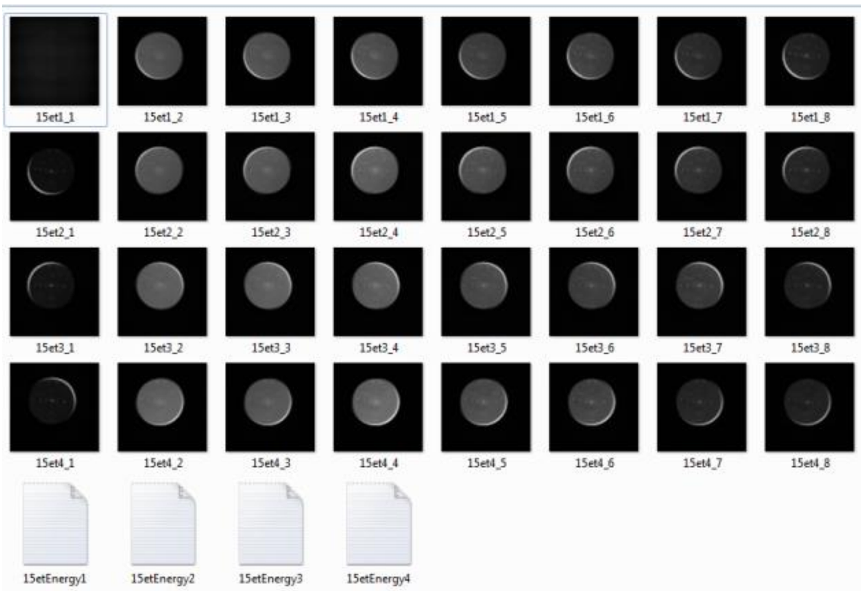


Figure 4.4: Matlab "IMAGES" folder containing the acquired 32 images and the energy values for each module.

Step3: Measuring the energy values for each LED and inserting them into the Matlab/IMAGES folder together with the 32images (this step is done only once).

Here are the values for the 4 corners of the dark room with the energy flux of each 8 LEDs in hexadecimal numbers for white light.

RGB LEDS	Panel 1	Panel 2	Panel3	Panel 4
LED1(top)	B7	E5	CC	A2
LED2	A8	E0	B6	99
LED3	A1	B8	AE	9A
LED4	9F	A2	AC	9B
LED5	9E	A8	AA	9E
LED6	A0	A5	AB	98
LED7	9E	A1	A0	98
LED8	A6	9E	AE	94

Table 4.1: Hexadecimal number of the energy flux values for white light.

Step 4: After the image acquisition we proceed to image evaluation.

4.1.2 LabView Block Diagram and Programming

In the flow chart below we can see the 8 steps of acquiring the images in LabView.

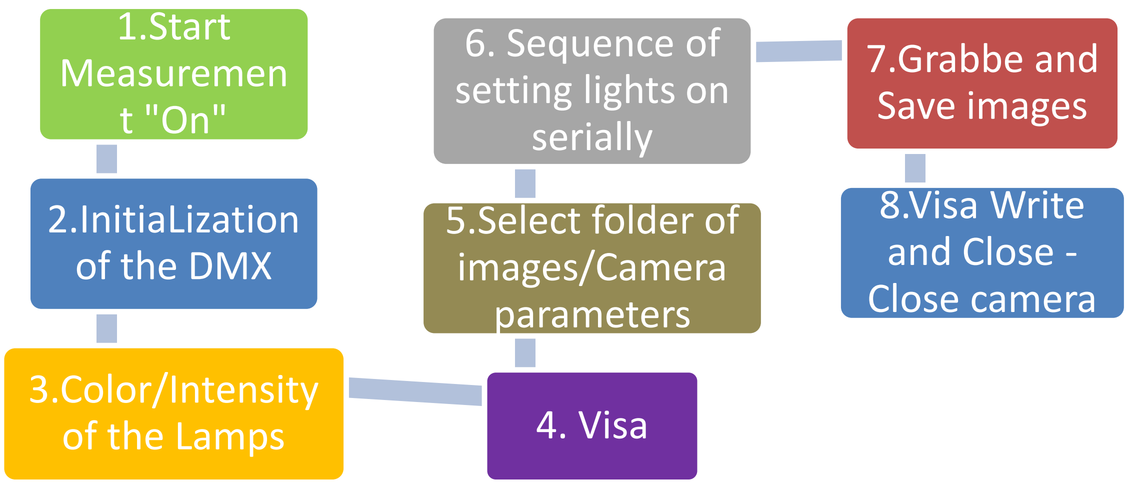


Figure 4.5: Flow chart of LabView programming.

The Block diagram of our new Labview is divided to 8 steps. The steps are outlined below:

Step1: Start Measurement

As already said, when setting the parameters the Labview programme cannot Run if the 'Start Measurement' button' is not ON. In Labview language this function is a Case structure with True of False values and the value wired to the selector terminal determines which case to execute. In our case Start Measurement "**True**" executes the programme.

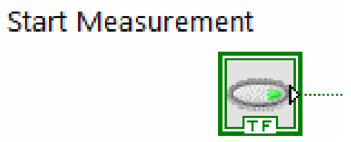


Figure 4.6: Start Measurement Icon in LabView

Step 2: The USB-DMX Initialization.

Then entering the sequence we insert the values for initializing the DMX interface. We create a 1D array with zeros in all 518 positions. Starting from position 0 which actually is the first element in our ID array we send 5 values (hexadecimal -7E numbers) to initialize the DMX . The interpretation of these numbers for DMX protocol is described below:

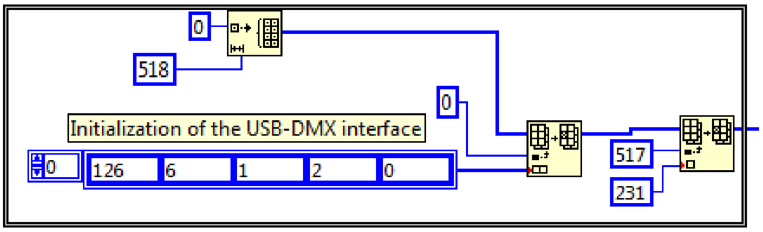


Figure 4.7: Initialization of the DMX interface in Labview.

hexadecimal 7E numbers	Description
126	Start Value
6	Start Output
1	Data Length of the Lest Significant Bit (LSB)
2	Data Length of the Most Significant Bit (MSB)
0	Separation of values

Table 4.2: Interpretation of hexadecimal 7E numbers for the initialization of DMX protocol.

Step3: Setting color and Intensity.

Next step is setting the parameters for the intensity of the lamps [0-255] and selecting the color in RGB color model. For red with highest intensity we send (255, 0, 0) for the color and 255 for intensity.

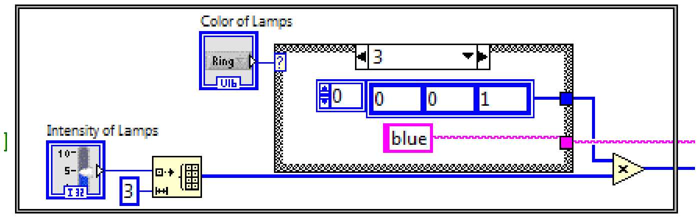


Figure 4.8: Selecting the color and the intensity of the lamps in Labview.

Then we select the serial port that connects our virtual device (COM7) to the computer using Visa.

Step 4: Visa

In the new Labview programme, we used VISA which is a standard I/O language for instrumentation programming. VISA is a high-level API that calls lower level drivers. One of VISA's advantages is that it uses many of the same operations to communicate with instruments regardless of the interface type. VISA provides interface independence. This can make it easy to switch interfaces and also gives users who must program instruments for different interfaces a single language they can learn. Another advantage of VISA is that it is an object-oriented language which will easily adapt to new instrumentation interfaces as they are developed in the future. VISA's greatest advantage, perhaps, is that it is an easy language to learn and use. Its object-oriented structure makes the language and its operations intuitive to learn.

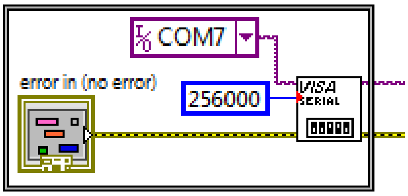


Figure 4.9: VISA block in Labview.

Step 5: Camera parameters.

In the picture below we can see the parameters and settings of the camera. Initialization of the camera / Reading and setting the exposure time and checking if the value is in between the limits / Read Set Meter Gain Variable. Before the programme is going to Run we select the folder that our images are going to be saved in and we name our measurement.

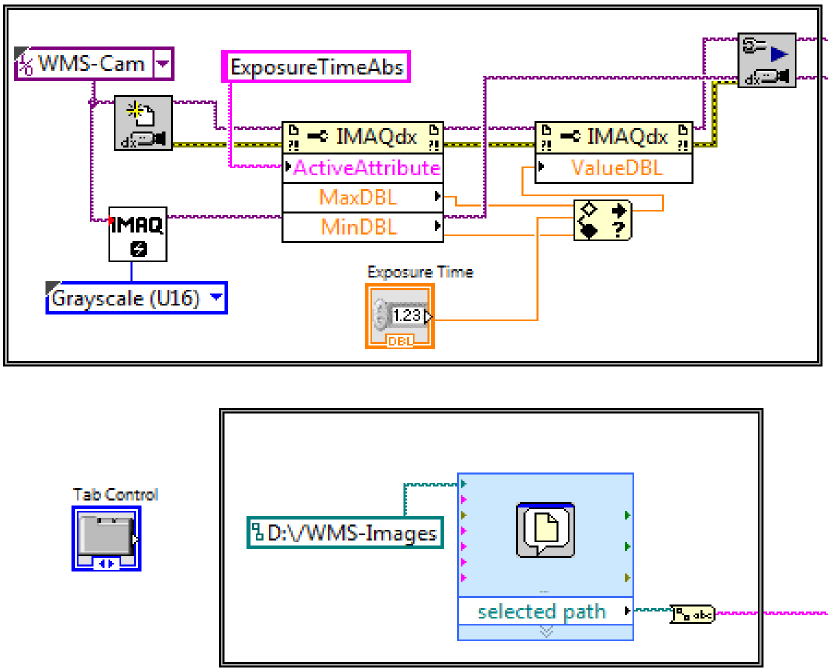


Figure 4.10: Setting camera parameters using IMAQdx (top image). Selection of the folder that the images will be saved in (bottom image).

Step 6: Iteration for turning LED lamps on serially.

Next step is that the data from the DMX protocol and camera initialization are inserted in a “For” loop (with 32 number iteration). First we have a 1D array with zeros inserted in the position 0 of another array along with the intensity value that we have already set. Then this data are shifted 3 positions and are sent to the fifth position of a new array. To turn one LED on at a time the array has to be sent 32 times and replace the previous array with the new shifted elements.

	Initialization					**First Shifting**			**LED1 (white)**			**LED2**		
Positions	**0**	**1**	**2**	**3**	**4**	5	6	7	8	9	10	11	12	13
Values	**126**	**6**	**1**	**2**	**0**	0	0	0	255	255	225	0	0	0

Table 4.3: Example of shifted values inside the For Loop

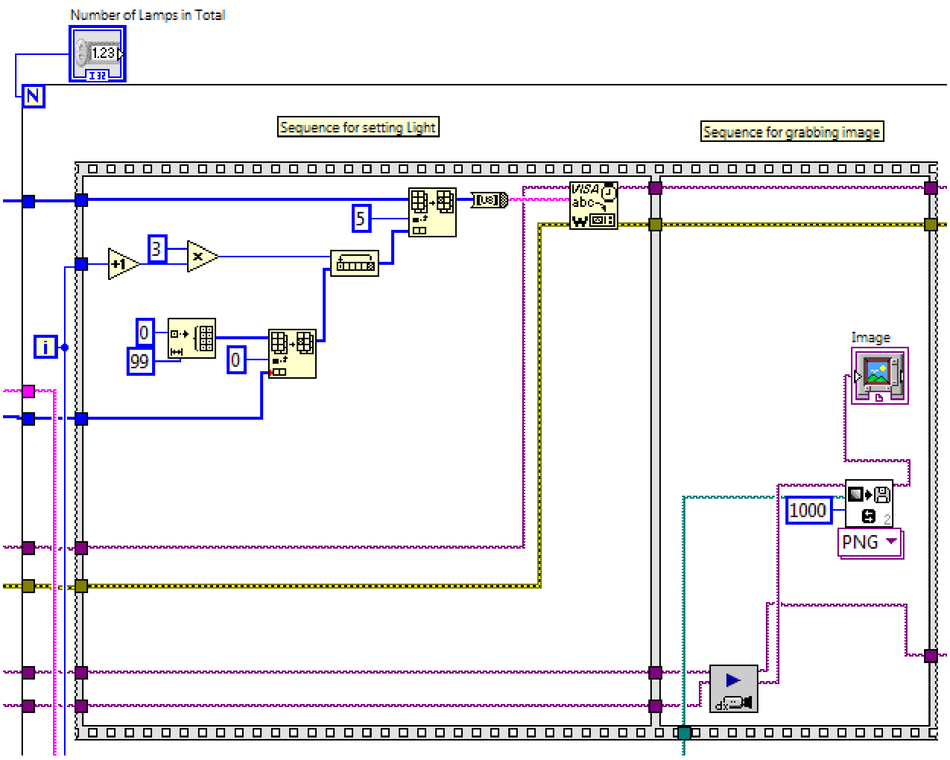


Figure 4.11: Shifting values inside a "For" Loop for 32 iterations.

Step 7: Name of the images

In every iteration we turn on a LED, record and image and save it in a specific format. For example if we named our measurement "trial" and the color we selected was white then the first photo will be named "trial_white_1_1" which means the first LED from the first module. So we will get 32 images starting from "trial_white_1_1.png" to "trial_white_4_8.png"

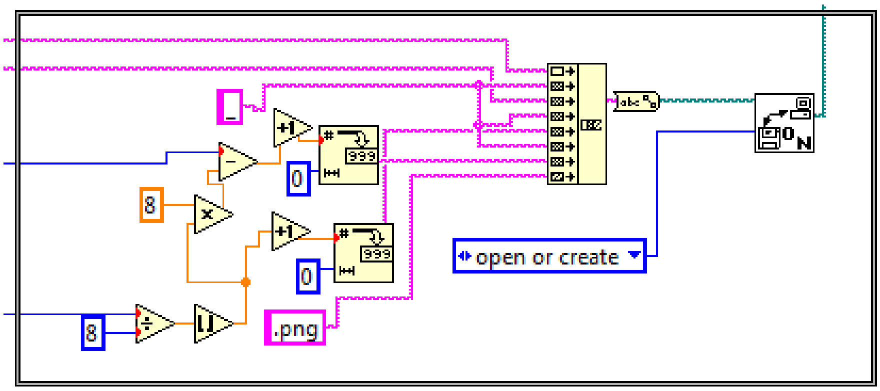


Figure 4.12: Saving images with specific name in the chosen folder.

Step 8: Close Visa and Camera

Finally we have Visa Write and Close, as well as the closing of the Camera when our programme is finished.

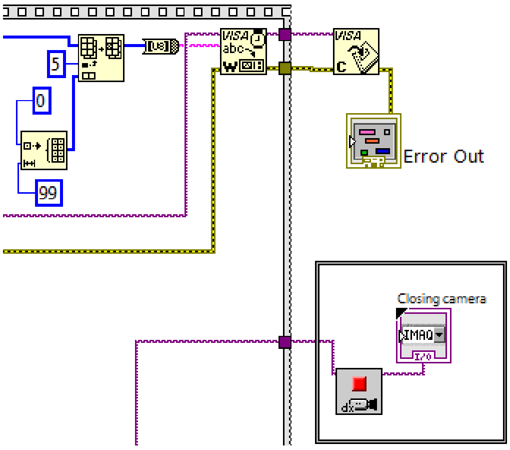


Figure 4.13: Visa Write/Close and Closing of the camera.

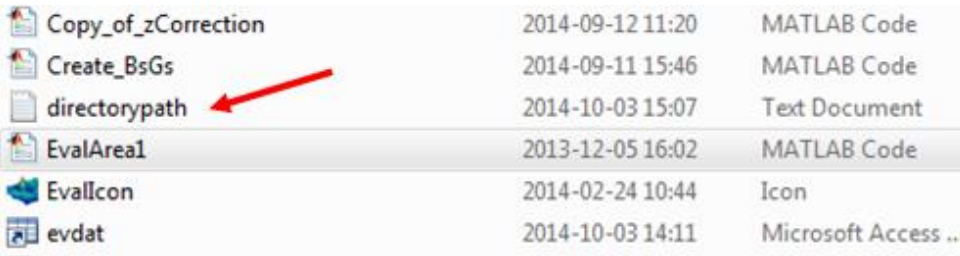
4.2 New Matlab

4.2.1 Initial Steps and Inserting new system coordinates.

After the image acquisition we proceed to the image evaluation. This as the old WMS is done with the Matlab Evaluation application. New Matlab is based on the old WMS – Matlab with changed system coordinates and number of total led lamps. Here are the steps for getting the surface profile of the evaluated area:

Step1: In Matlab programme we change the name from the "directorypath.txt" file with the name of our measurements. (D:\WMS-IMAGES\ **15et**).

In the Matlab folder we should change the directory path which is the path of inserting the acquired images to the Matlab. So in this case, from the "directorypath.txt we write the name of the folder and the name of the images that we took. In any other case the Matlab will not run.



Copy_of_zCorrection	2014-09-12 11:20	MATLAB Code
Create_BsGs	2014-09-11 15:46	MATLAB Code
directorypath	2014-10-03 15:07	Text Document
EvalArea1	2013-12-05 16:02	MATLAB Code
EvalIcon	2014-02-24 10:44	Icon
evdat	2014-10-03 14:11	Microsoft Access ..

Figure 4.14: Matlab 'directory path' document for setting the name of the images that we are going to evaluate.

The Matlab application that I worked with included 20 different m.file codes which were changed and adopted to the new 8 LED panel system.

Step2: In the new WMS system we have 8 LEDs compared to 5 flash lights in each module. Moreover, the LED panel is positioned at different heights than the flash lights were. For this reason, x-axis, y-axis and z-axis have to be inserted in the new array. In the tables below we can see the new parameters that were inserted in the new upgraded Matlab Evaluation programme:

The arrangement of the measuring system or to be precise, the positioning of the camera and the four modules determine the coordinate system that is used for the evaluation. A schematic top view within the coordinate system can be seen in the following figure:

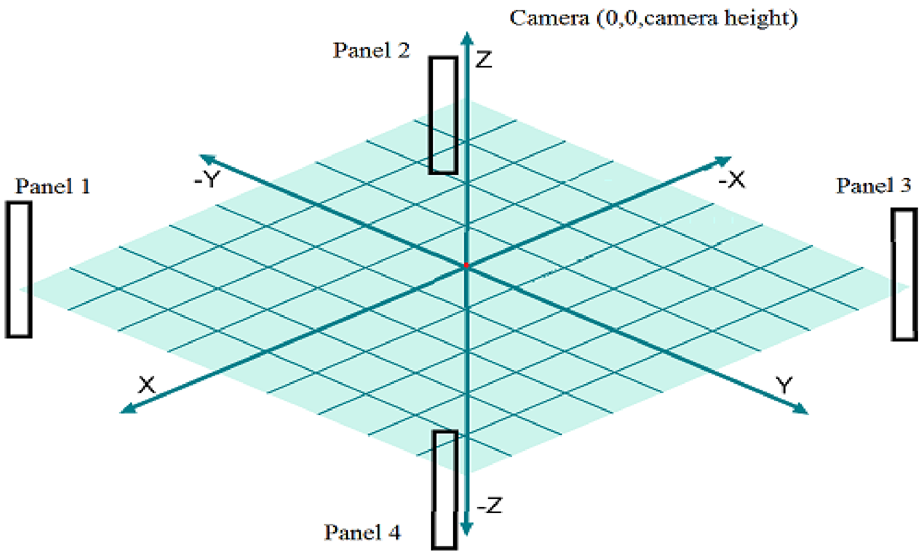


Figure 4.15: The new coordinate system(x, y, and z-axis) for the LED RGB lamps.

As one may recognize, the camera is located at the z-axis in position (0, 0, camera height), what means that the point of origin is on floor level. The four modules should ideally be placed in the corners with equal distances to the z-axis.

Specific physical parameters such as position of each LED lamp and camera or the average height of the table are introduced in the parameter file which is saved as an m-file and then in turn these parameters are saved in a dat-file. If we don't adjust these parameters systematic errors might influence the results. In the par.file named **'WMSPar_active.par'** we save the X, Y, Z positions and the camera calibration parameters.

X-flash

	module1	module2	module3	module4
Led1	1,38	– 1,38	– 1,38	1,38
Led2	1,36	– 1,36	– 1,36	1,36
Led3	1,34	– 1,34	– 1,34	1,34
Led4	1,32	– 1,32	– 1,32	1,32
Led5	1,30	– 1,30	– 1,30	1,30
Led6	1,28	– 1,28	– 1,28	1,28
Led7	1,26	– 1,26	– 1,26	1,26
Led8	1,24	– 1,24	– 1,24	1,24

Table 4.4: X-direction values for the 8 LEDs.

Y-flash

	module1	module2	module3	module4
Led1	– 1,38	– 1,38	1,38	1,38
Led2	– 1,36	– 1,36	1,36	1,36
Led3	– 1,34	– 1,34	1,34	1,34
Led4	– 1,32	– 1,32	1,32	1,32
Led5	– 1,30	– 1,30	1,30	1,30
Led6	– 1,28	– 1,28	1,28	1,28
Led7	– 1,26	– 1,26	1,26	1,26
Led8	– 1,24	– 1,24	1,24	1,24

Table 4.5: Y-direction values for the 8 LEDs.

Z-flash

	module1	module2	module3	module4
Led1	1,00	1,00	1,00	1,00
Led2	1,11	1,11	1,11	1,11
Led3	1,22	1,22	1,22	1,22
Led4	1,33	1,33	1,33	1,33
Led5	1,44	1,44	1,44	1,44
Led6	1,55	1,55	1,55	1,55
Led7	1,66	1,66	1,66	1,66
Led8	1,77	1,77	1,77	1,77

Table 4.6: Z-direction values for the 8 LEDs.

*In meters

Step 3: Then we read the images for each module and the energy values from the text.files.

```
% Read Images and Energylevels


% ------------------ IMAGES --------------------

dir = strcat(dipa,'1_1.png');
A1 = double(imread(dir));
dir = strcat(dipa,'1_2.png');
A2 = double(imread(dir));
dir = strcat(dipa,'1_3.png');
A3 = double(imread(dir));
dir = strcat(dipa,'1_4.png');
A4 = double(imread(dir));
dir = strcat(dipa,'1_5.png');
A5 = double(imread(dir));
dir = strcat(dipa,'1_6.png');
A6 = double(imread(dir));
dir = strcat(dipa,'1_7.png');
A7 = double(imread(dir));
dir = strcat(dipa,'1_8.png');
A8 = double(imread(dir));
```

```
% ------------------ Energylevels ----------------
dir = strcat(dipa,'Energy1.txt');

fid = fopen(dir,'r');

Energy = (fscanf(fid,'%x %x %x %x %x %x %x %x'))';

fclose(fid);


Energy = (Energy./4095).*(2^16);

A1 = A1./Energy(1);
A2 = A2./Energy(2);
A3 = A3./Energy(3);
A4 = A4./Energy(4);
A5 = A5./Energy(5);
A6 = A6./Energy(6);
A7 = A7./Energy(7);
A8 = A8./Energy(8);
```

Figure 4.16: Images and energy levels in the Matlab code "Read_WMS_Img1".

Step 4: Running the Matlab Evaluation application. ('WMSEvaluation').

At this stage, the area we want to evaluate is selected and cropped. We have the possibility either to select the whole image or a small area. The bigger the evaluated area the more time the application needs to give the results. The Matlab evaluation time takes 2-5 minutes approximately.

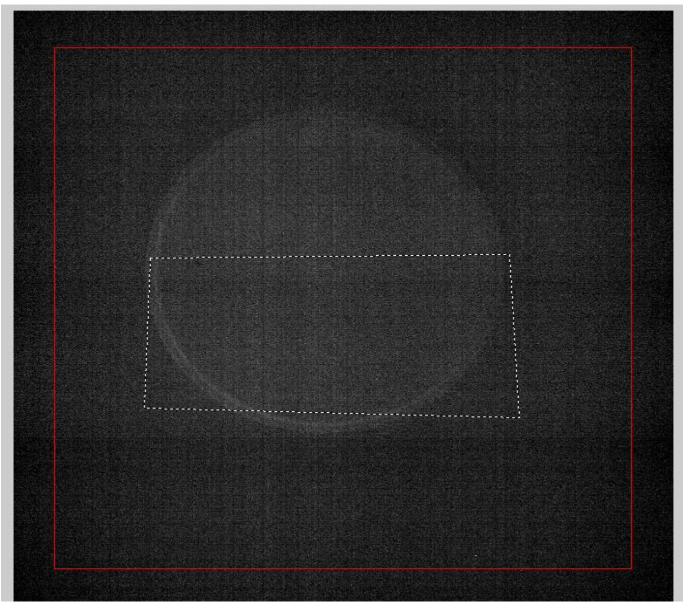


Figure 4.17: Selecting the area and cropping.

Step5: Calculation and Results.

At this stage the application software calculates the alpha slopes and height profile before giving the evaluated surface. After that we can use the red and blue subtraces to get the profile of the area. As we can see in the Figure 4.5 we will get the minimum (MIN), maximum (MAX), Peak to Peak (PTP) and Root Mean Square (RMS) values. Finally we can get the 3D image of the evaluated area.

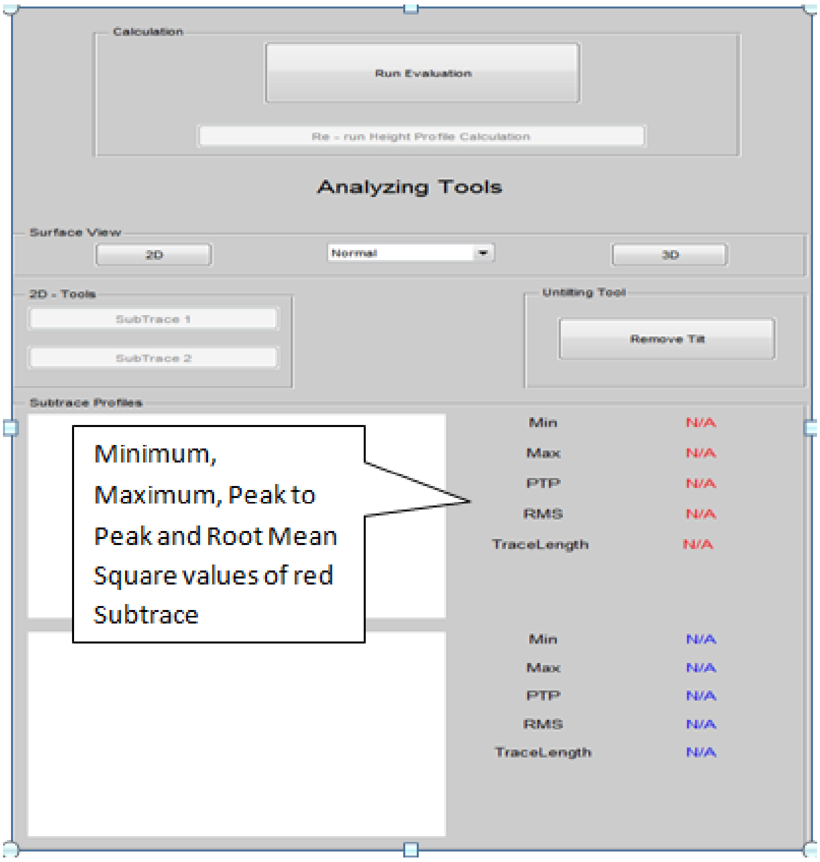


Figure 4.18: Evaluation interface in Matlab.

4.2.2 Image Processing – Calculating angles

A. Beta calculation

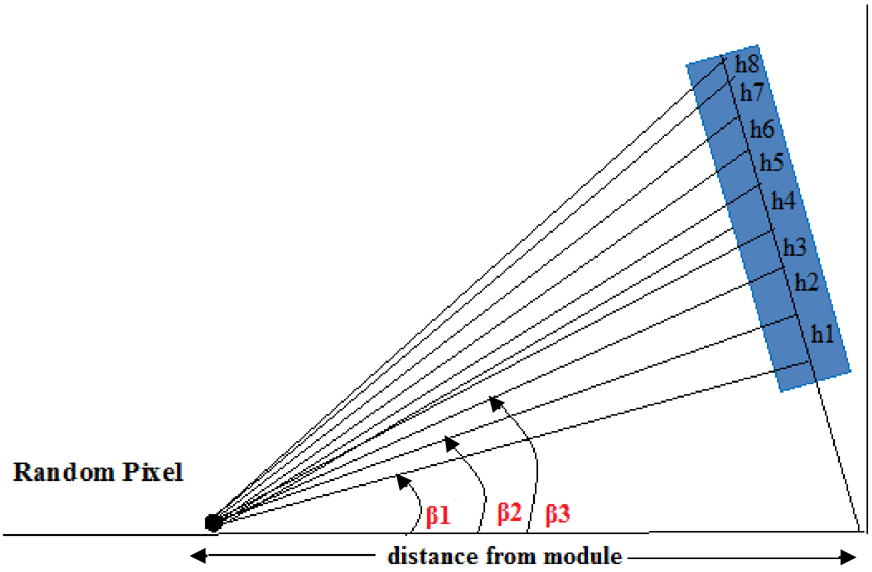


Figure 4.19: Calculation of β from random pixel and four modules

The distances can be acquired through a pixels position and the positions of the modules in the coordinate system, whereas the flash lamps' heights are computed by subtracting the average height from the measured heights of the flashes, which should be written in the parameter file. Finally, the different β – angles for a random pixel Px,y are calculated from

$$\beta_{x,,\ 1\ldots4, Flash\ Lamp\ 1\ldots5} = \textbf{arctan}\left(\frac{\text{heightFlashLamp }1\ldots5}{\text{distanceModule }1\ldots4}\right) \quad (4.1)$$

Where x and y are coordinates of the current pixel, but not equal to n for columns and m for rows of the image matrix (P0, 0 is the central pixel, not the one in the upper left corner).

B. Calculation of γ (gamma) – angles

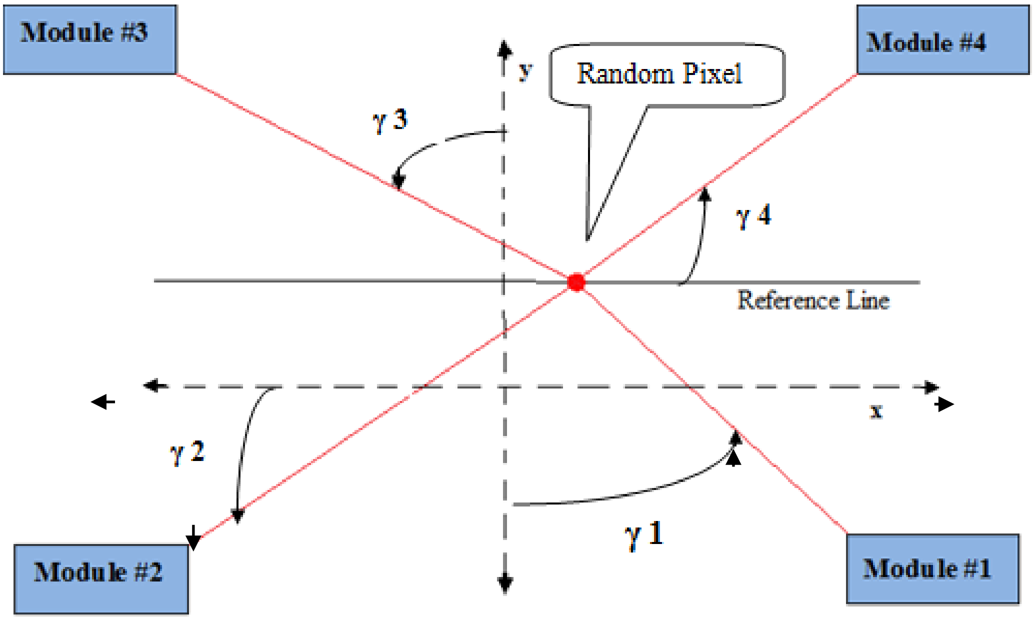


Figure 4.20: Calculation of γ-angles for a random pixel.

The γ – angles represent the direction from a pixel towards each module with respect to a reference line, which runs parallel to the x-axis, as it can be seen in figure 4.20. They're calculated with the following equations, assuming Px,y (xP, yP) is the current pixel:

$$\gamma 4 = \arctan\left(\frac{|y4-yp|}{|x4-xp|}\right) \qquad (4.2)$$

$$\gamma 3 = \arctan\left(\frac{|y3-yp|}{|x3-xp|}\right) + \frac{\pi}{2} \qquad (4.3)$$

$$\gamma 2 = \arctan\left(\frac{|y2-yp|}{|24-xp|}\right) + \pi \qquad (4.4)$$

$$\gamma 1 = \arctan\left(\frac{|y1-yp|}{|x1-xp|}\right) + \frac{3}{2}\pi \qquad (4.5)$$

It is obvious that the amounts of data for these calculations are rather large; since there are 32 β – and 4 γ – angles for every single pixel, which is all in all 2048 x 2048. But as a matter of fact, once the system is calibrated and the parameter file accordingly adjusted, the values are constant and thus can be pre-calculated and stored in a file.

C. Reading β and γ – Angles

In the new upgraded 8 LED panel system, we get 32 β angles and 4 γ angles which indicated the distance of the pixel from each module.

```
% read betas and gammas

filename = 'angle_values.par';
fid = fopen(filename,'r');

B1 = zeros(VPIXEL,HPIXEL,8);
B2 = zeros(VPIXEL,HPIXEL,8);
B3 = zeros(VPIXEL,HPIXEL,8);
B4 = zeros(VPIXEL,HPIXEL,8);
C_m = zeros(VPIXEL,HPIXEL,4);


B1(:,:,1) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,2) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,3) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,4) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,5) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,6) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,7) = fread(fid,[VPIXEL HPIXEL],'double');
B1(:,:,8) = fread(fid,[VPIXEL HPIXEL],'double');
```

Figure 4.21: Reading of betas and gammas in Matlab code.

Firstly, the slopes α, which are the slopes in each of the four directions, are calculated for every surface element or rather every pixel of the images. For this purpose, it is necessary to evaluate the angles β between the measurement table and the led lamps, as well as the angles γ that indicate the direction of each pixel towards the four modules in the first instance. The following figure shows the example, how the angles are calculated for a random pixel and each of the four modules. As one can see, they can be easily evaluated with trigonometric equations, given the distance between pixel and module and the height of the respective led lamps.

D. Calculation of the α-slopes.

The measurement can be accomplished once all needed values are acquired. The next step is to evaluate the slopes of each surface element towards the four modules, which are called α-slopes or α-angles. These are calculated in the following procedure:

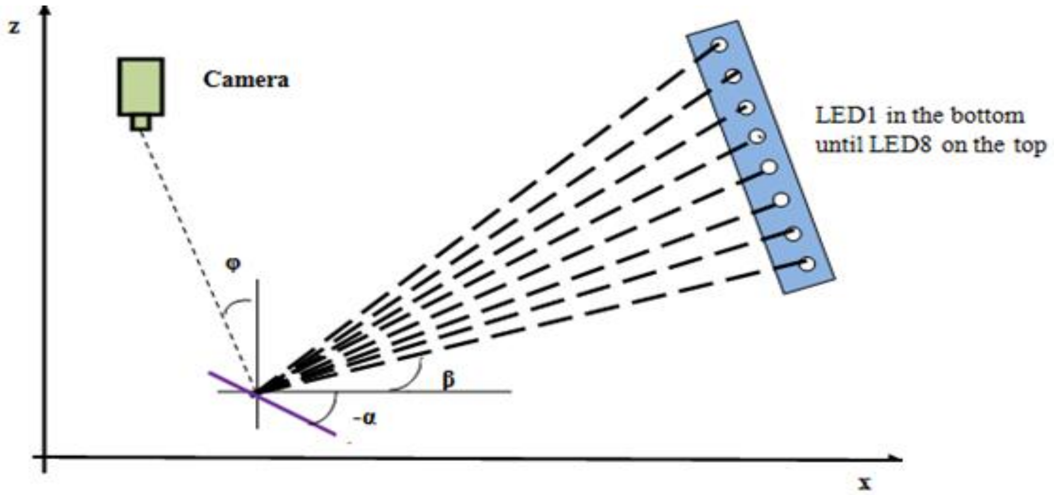


Figure 4.22: Illumination of the surface with slope α from different β.

This is applied for each of the four modules.

A surface is illuminated from different angles by flash lamps and one image per flash is taken with the camera. The grey-values of pixels in images can be considered as the measured radiant intensity Icamera that is reflected by the surface elements in the camera's direction. Therefore, the exposure from a flash on one camera pixel can be expressed as

$$\mathbf{I}_{camera} = \mathbf{const}1 * \mathbf{R}_{surface} * \mathbf{f}_{scattering}\,(\Phi, \beta\text{-}\alpha) * \mathbf{I}_{lamp} \qquad (4.6)$$

Where:

const1 is a constant for the current surface element

$\mathbf{R}_{surface}$ is the reflectance of the current surface element

$\mathbf{f}_{scattering}$ is the scattering function for the current surface element

$\mathbf{I}_{lamp}$ is the radiant intensity of the flash lamp

The measured surfaces are assumed to be diffuse, for that reason the scattering function becomes:

$$\mathbf{f}_{scattering}\,(\Phi, \beta\text{-}\alpha) = \cos\Phi * \sin(\beta\text{-}\alpha) \qquad (4.7)$$

According to Lambert's Cosine Law, since the angle Φ is constant for every surface element the reflectance coefficient equation can be stated as

$$\mathbf{I}_{camera} = C1 * \sin(\beta - \alpha) * \mathbf{I}_{lamp} \qquad (4.8)$$

In this case a normalized image is

$$\mathbf{I}_{norm} = \frac{Icamera}{Ilamp} = C1 * \sin(\beta - \alpha) \qquad (4.9)$$

Where *C1* is a constant for the current surface element, but not equal to *const1* due to the influence of $R_{surface}$ and the camera's direction angle Φ. It also may contain the distance from the pixel to the respective flash lamp.

I_{lamp} is measured with the energy sensors for every flash lamp. As it can be seen, there is a linear relation between the normalized radiant intensity and the scattering function, which is displayed in the figure below.

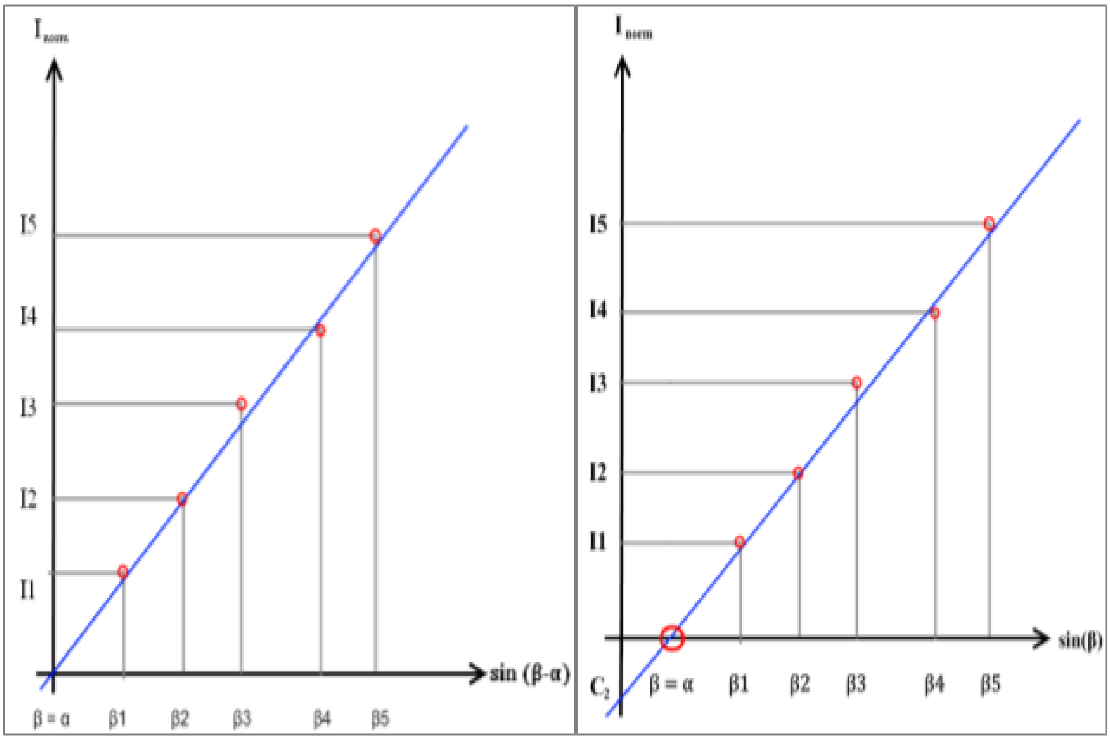


Figure 4.23: (Left graph) Relation between I_{norm} and scattering function, (Right graph) Relation between I_{norm} and shifted scattering function.

Technically, if the incident light comes from an angle equal to the surface's slope (β = α), no light will be reflected and therefore, the radiant intensity is approximately 0. This fact is used to compute the α – angles, for what it is necessary to shift the function first:

$$I_{norm} = \boldsymbol{C1} \cdot \sin(\beta) + \boldsymbol{C2} \qquad (4.10)$$

Where C2 is the radiant intensity, if $\beta = 0$.

The graph can be seen in Figure 4.23 (right graph).

The measured values (red circled) are extrapolated by linear regression (blue line) that gives the values for both constants C1 and C2. These are used to find the intersection point with the abscissa or to be precise, to finally obtain the α-slope of the surface element in the direction to the particular module position. That means there are all in all four slope-values per pixel.

It is obvious that the calculation is inexact, since ideal diffuse reflection is assumed. In reality, the measured values mostly show a non-linear behavior, for instance, when surfaces become reflective for small angles of incidence or to the contrary, "if the lamp reflex gets into the camera field of view for large angles"4. Nonetheless, the linear extrapolation is still done, but may need an adjustment, so that outliers can be eradicated beforehand.

E. Evaluation of the a angles in x and y direction (a_x, ay)

Now that the slopes (α) of each pixel and their respective directions (γ) are known, it is possible to evaluate the slopes in x-and y-direction. This can be achieved by solving the equation system below:

$$\alpha x = \frac{\sum_{m=1}^{4}[am * \cos(\gamma m)]}{\sum_{m=1}^{4} cos^2(\gamma\mathrm{m})} - \mathrm{ay} * \frac{\sum_{m=1}^{4}[\sin(\gamma m) * \cos(\gamma m)]}{\sum_{m=1}^{4} cos^2(\gamma\mathrm{m})} \qquad (4.11)$$

$$\alpha y = \frac{\sum_{m=1}^{4}[am * \cos(\gamma m)]}{\sum_{m=1}^{4} sin^2(\gamma\mathrm{m})} - \mathrm{ax} * \frac{\sum_{m=1}^{4}[\sin(\gamma m) * \cos(\gamma m)]}{\sum_{m=1}^{4} cos^2(\gamma\mathrm{m})} \qquad (4.12)$$

```
function [ax , ay] = x_y_slope(alpha,C,x,y)

% Calculation of the slope in x- & y-direction

u1 = sum(alpha(y,x,:).*cos(C(y,x,:)))/sum((cos(C(y,x,:))).^2);
u2 = sum(sin(C(y,x,:)).*cos(C(y,x,:)))/sum((cos(C(y,x,:))).^2);

v1 = sum(alpha(y,x,:).*sin(C(y,x,:)))/sum((sin(C(y,x,:))).^2);
v2 = sum(sin(C(y,x,:)).*cos(C(y,x,:)))/sum((sin(C(y,x,:))).^2);

ax = (u1-v1*u2)/(1+v2*u2);
ay = (v1-u1*v2)/(1+v2*u2);
```

Figure 4.24: Calculation of the a slopes in x and y directions in Matlab code.

Where

m is the module number (1..4)

γ_m are the directional angles in respect to the module number m

a_m are the slopes of the pixel in the directions γm

It turns out to be advantageous that the surface is illuminated from opposite directions (m=1 to m=3, m=2 to m=4), because errors in ax and ay are thereby eliminated at it was described before.

F. Evaluation of the height profile

The final step is to evaluate the z-positions or the height of every single pixel in order to get the three-dimensional shape of the measured surface. Therefore, an iterative procedure is used, which includes the following steps:

1. All the pixels get an initial height z, which is 0 at first run.
2. Each pixel is tilted according to their slopes ax and ay that were computed before. For better comprehension see the figure below.

The heights of the pixels four edges (z1..z4) are calculated, where z1= -z3 and z2=-z4

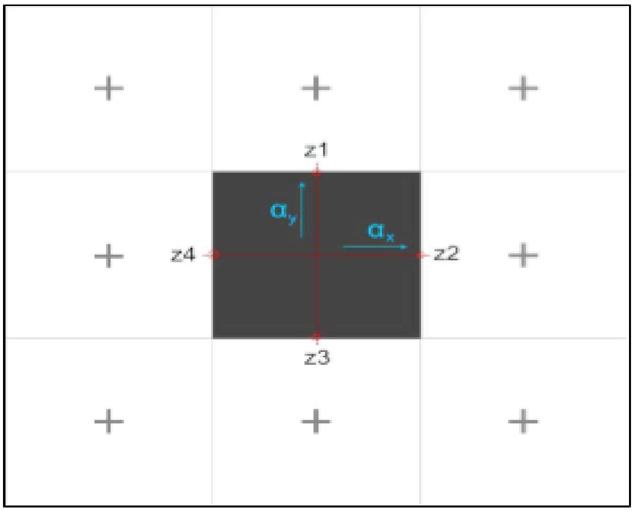


Figure 4.25: Tilting of a pixel Px,y

1. All four edges of each pixel (Pxy) are compared with the respective edges of their neighbors (Px+1,y ,Px-1,y,Px,y+1,Px,y-1) , that means z1(x,y) with z3(x-1,y), z2(x,y) with z4(x+1,y), z3(x,y) with z1(x,y+1) and z4(x-1,y). Afterwards, a height correction value is computed is computed through the mean height difference of all four edges.
2. The new z-position for all pixels is determined by adding the initial height and the calculated height correction, what gives the initial height for the next iteration.
3. The iteration needs to be repeated many times for the purpose to get a satisfying accuracy, what results in a long evaluation process. Due to that fact, the system was sped up through a small change in the procedure outlined above.
4. The idea is to carry out this procedure on larger surface elements (e.g. 128x128 pixels) first. These big pixels are tilted by the mean slopes ax and ay of all pixels they contain and treated in implied manner, which gives initial height values for two times smaller surface elements (in that case 64x64pixels) and so on.

Chapter 5

5.1 Measurements - Description

In this chapter we report on the measurements after the improvement of Labview and the changes we made in Matlab. First of all, the measurements are divided into three categories. First set of measurements is different color or type of surface. Specifically we took measurements on yellow and orange polished panels, black metal sheet surfaces, grey metal sheet surface (unpolished), white plastic surface and a metal tool. The second stage was to illuminate the samples with different colored light. Starting with white and then with RBG (Red, Green, Blue). Finally for each surface and color we took measurements for different exposure times like 10.000,15000,30000 and 50000.The last two stages were set from the front panel of Labview, then the images were saved in the Matlab images folder together with the txt.files of the energy sensors which are expected to be the same for all measurements due to the fact that all LEDs have stable radiant flux/intensity every time we run the project. For this reason, this is why flash lights were replaced by LEDs.

In the table below we can see the different parameters of the measurements:

Surfaces	Red	Green	Blue	White
Yellow metal, Orange metal, Black metal, Grey metal, White plastic, metal tool	Exposure times (ms): 10000 15000 30000 50000	Exposure times (ms): 10000 15000 30000 50000	Exposure times (ms): 10000 15000 30000 50000	Exposure times (ms): 10000 15000 30000 50000

Table 5.1: Setting different parameters for the measurements.

5.2 Surfaces

5.2.1 Yellow Metal

The surface should be properly illuminated in order to get the best image sharpness. As seen in the surface images below recorded under white LED illumination the exposure time plays a major role. Exposure times 30000ms and 50000ms yield different resolution because more photons strike on the surface for long exposure times and the camera acquires better shadowing effects. In order to compare the results the area of evaluation is the same.

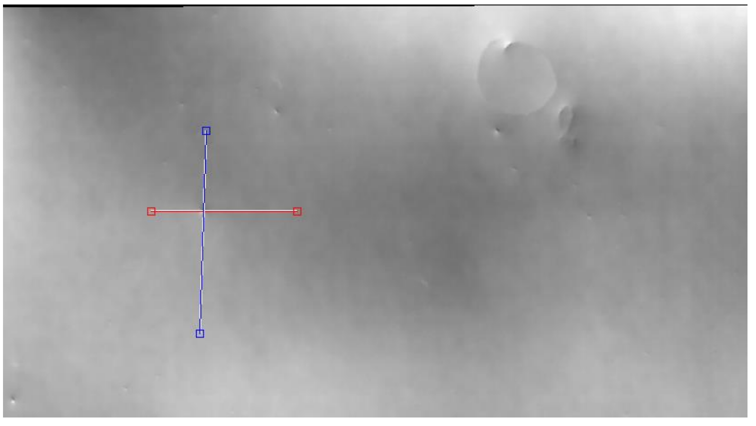


Figure 5.1: Yellow surface with 30000ms exposure time.

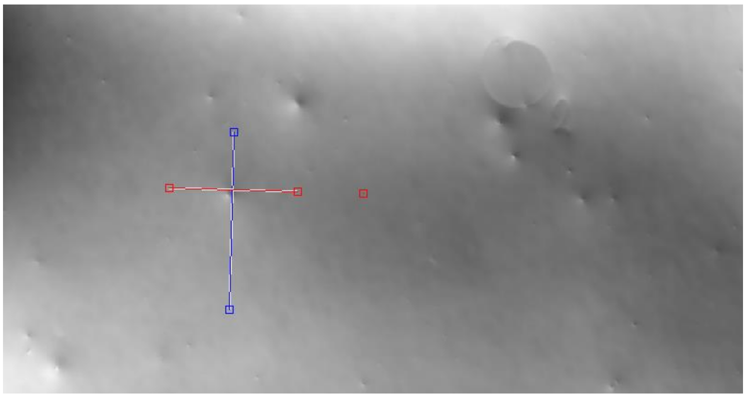


Figure 5.2: Yellow surface with 50000ms exposure time.

In detail:

	Exposure time 30000ms		**Exposure time 50000ms**	
Minimum (µm)	-40.18	-35.79	-50.52	-62.59
Maximum (µm)	23.93	11.73	8.79	41.55
PTP (µm)	64.11	47.52	59.31	104.14
RMS (µm)	11.15	11.03	21.85	26.46
Area (mm)	23.82	32.95	22.96	31.59

Table 5.2: Profile details for measurements with 30000 and 50000ms exposure time for yellow metal surface illuminated with white light.

As mentioned, the images taken with 50000ms exposure time are sharper because the sample is better illuminated. For the same area of evaluation (subtraces) of 23µm horizontal trace and 30mm perpendicular trace we can see that the maximum peak is 9µm for 50000ms compared to 23µm for 30000ms.

Results below are for blue LED illumination of the yellow surface at different positions within the same sample with exposure time 15000ms

Position1 (elevation):

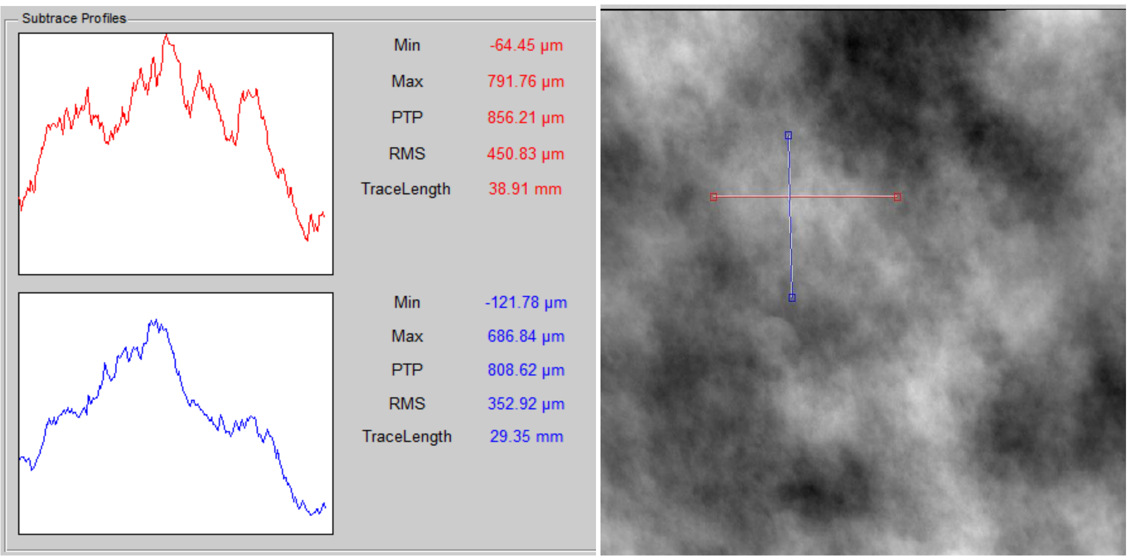


Figure 5.3: 2D image of the yellow metal surface illuminated with blue light for 15000ms exposure time, position1. On the right side there are the two subtraces' details.

The acquired picture is in grey scale. As we can observe elevations are brighter (almost white or light grey) while hollows are darker (almost black).

Position 2 (hollow):

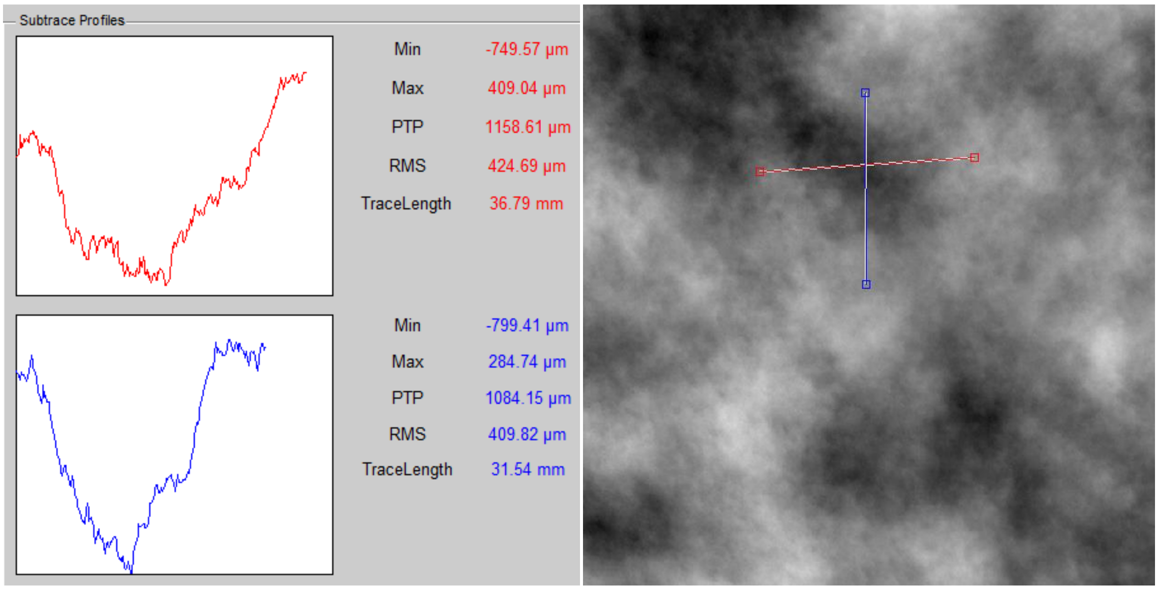


Figure 5.4: 2D image of the yellow metal surface illuminated with blue light for 15000ms exposure time, position2. On the right side there are the two subtraces' details.

As we can see on the same surface we can find both hollows and elevations. In the above measurement the hollow had almost 0.41mm depth while the elevation on another position on the same sample had 0.79mm height. This can be easily depicted in the 3-D image below. The yellow-reddish areas indicate that there are elevations whilst the dark blue ones that there is a hollow. The blue colored areas are places with deeper profile whilst yellow-red areas are with higher height.

3D-Image:

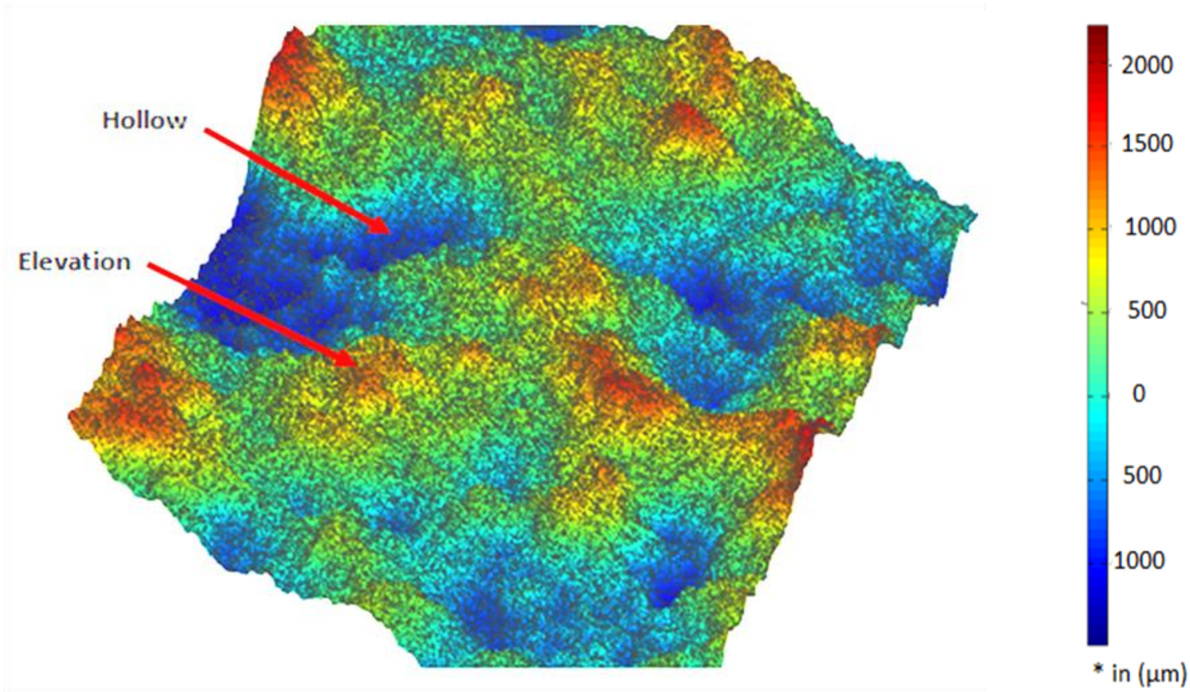


Figure 5.5: 3D image of the yellow metal surface with 15000ms exposure time for blue light.

5.2.2 Orange Metal

White color, Exposure time = 10000ms.

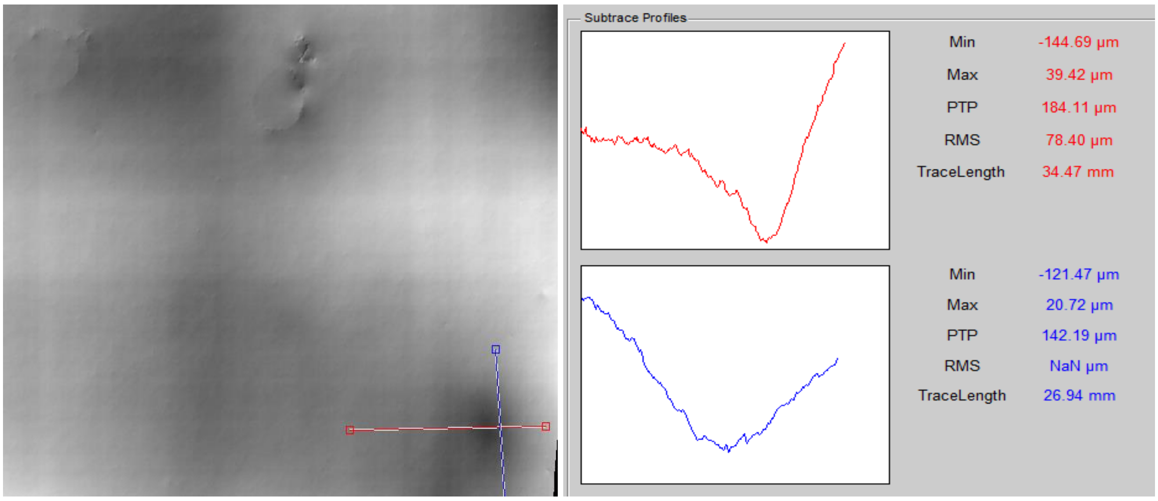


Figure 5.6: 2D image and subtrace details for an orange metal surface illuminated with white light for an exposure time of 10000ms.

Exposure time = 50000ms

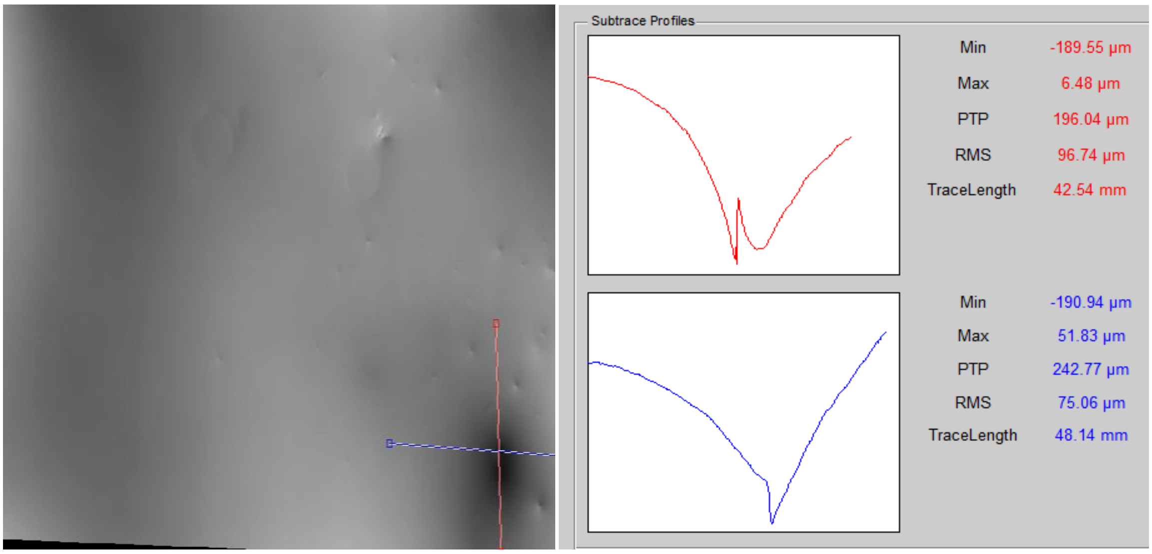


Figure 5.7: 2D image and subtraces details for an orange surface illuminated with white light for an exposure time of 50000ms.

For these measurements with orange metal surfaces using white light for the same position of evaluation we get 144µm depth for the measurement with 10000ms exposure time while we get 189µm depth for the 50000ms exposure time. In the second case the depth is higher almost 50µm difference which has to do with the change in the exposure time.

3D-Image:

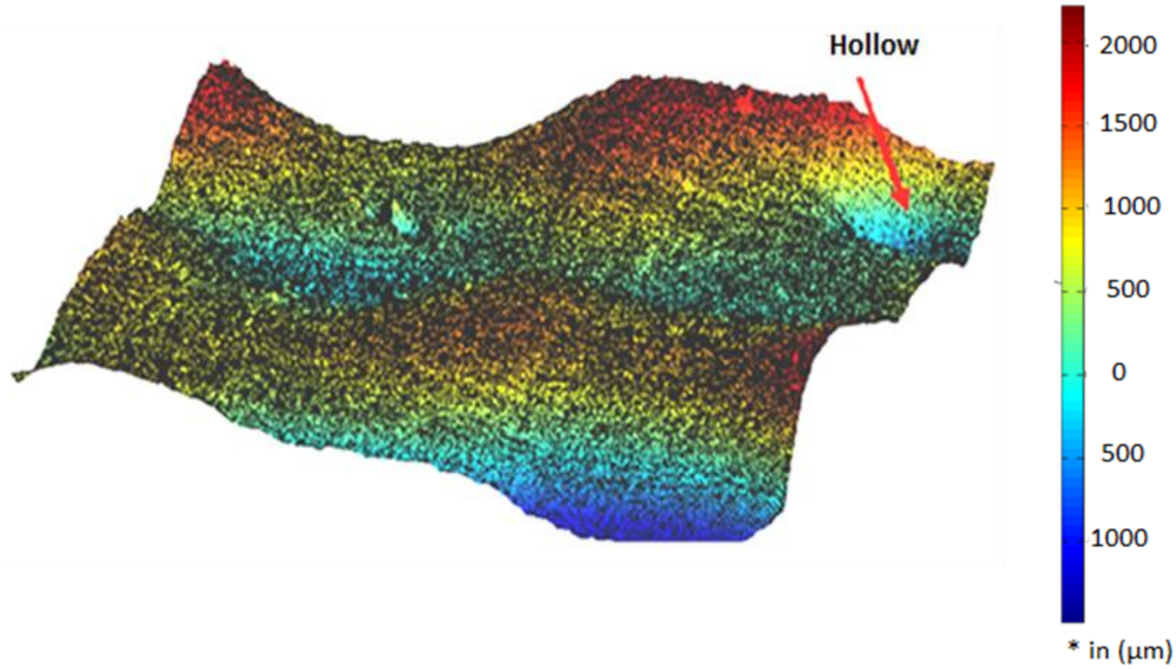


Figure 5.8: 3D image for an orange metal surface illuminated with white light for an exposure time of 10000ms.

Color = Green, Exposure time = 10000ms

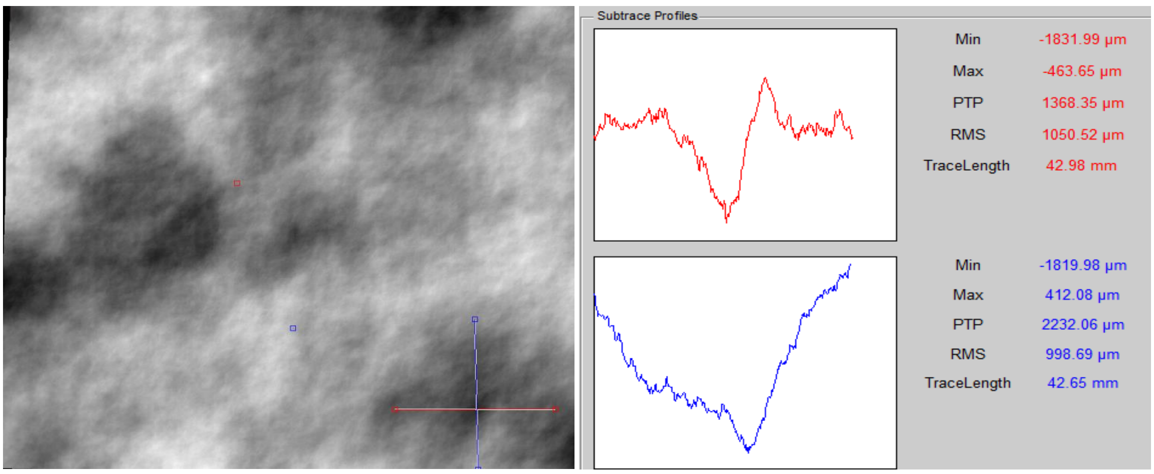


Figure 5.9: 2D image and subtrace details for an orange metal surface illuminated with green light for an exposure time of 10000ms.

Exposure time = 15000ms

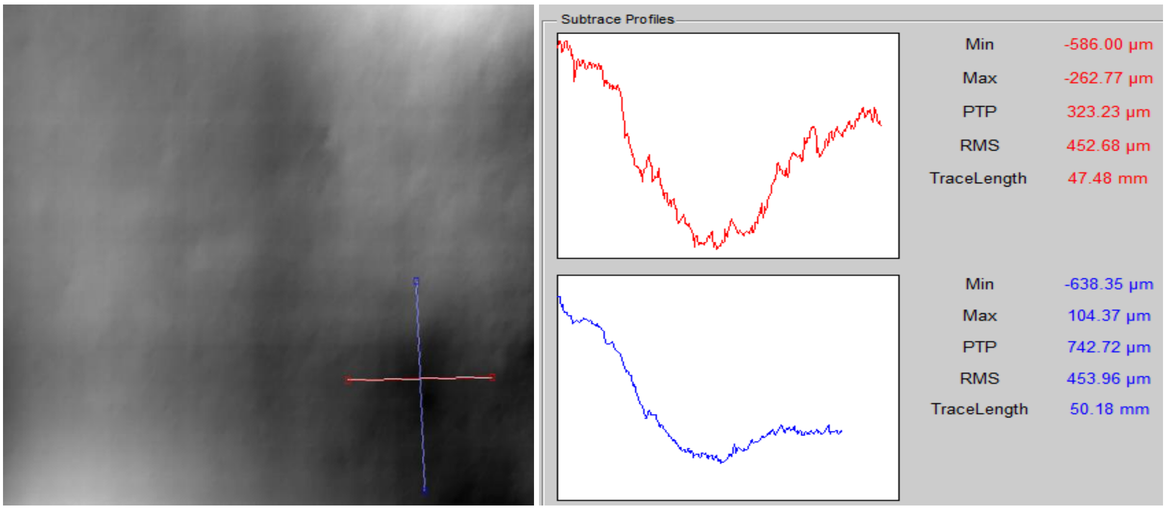


Figure 5.10: 2D image and subtrace details for an orange metal surface illuminated with green light for an exposure time of 15000ms.

First, we investigated the profile of the evaluated area with white light. In this measurement we get the profile when the surface is illuminated with green light. For the same exposure time (10000ms) the depth of the area with green light is 1.8mm compared to 0.2mm for the measurement with white light. So green light demonstrates better detail accuracy than white light for the orange surface. Moreover, if we increase the exposure time of the system to 15000ms for green light, more photons are absorbed in the surface so the depth is 586μm.

*It should be noted that there are small differences in the measurements regarding the trance length. (35mm for the white light and 42mm for the green light).Differences though are very small.

5.2.3 Grey Metal

Blue light, Exposure time =15000ms

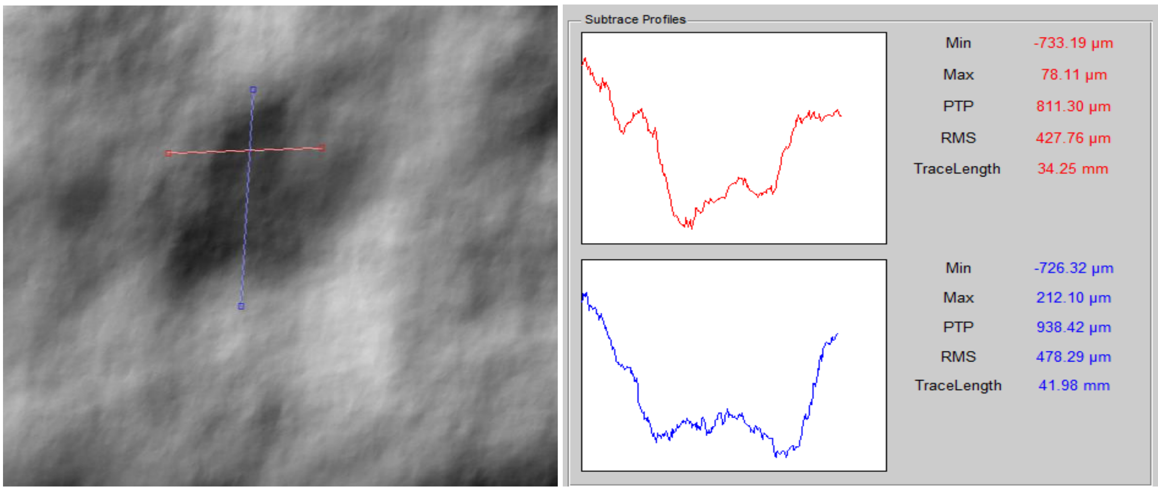


Figure 5.11: 2D image and subtrace details for a grey metal surface illuminated with blue light for an exposure time of 15000ms.

3D-image

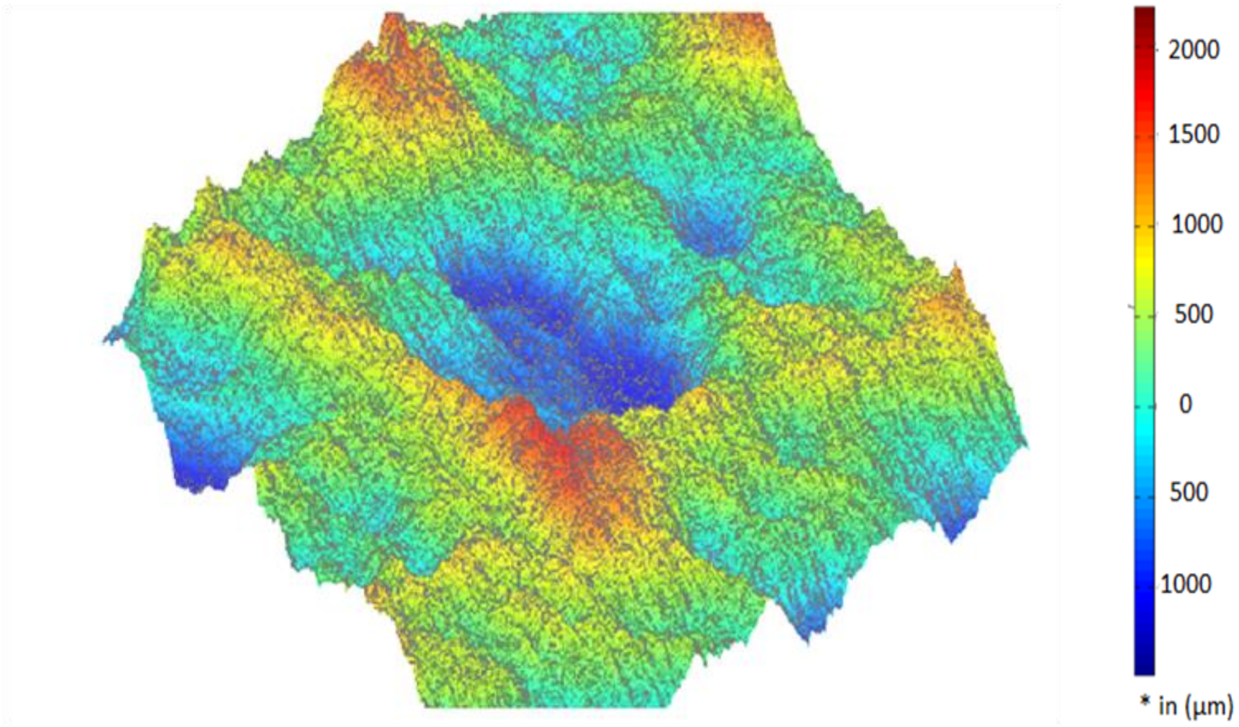


Figure 5.12: 3D image and subtrace details for a grey metal surface illuminated with blue light for an exposure time of 15000ms.

For exposure time = 50000ms

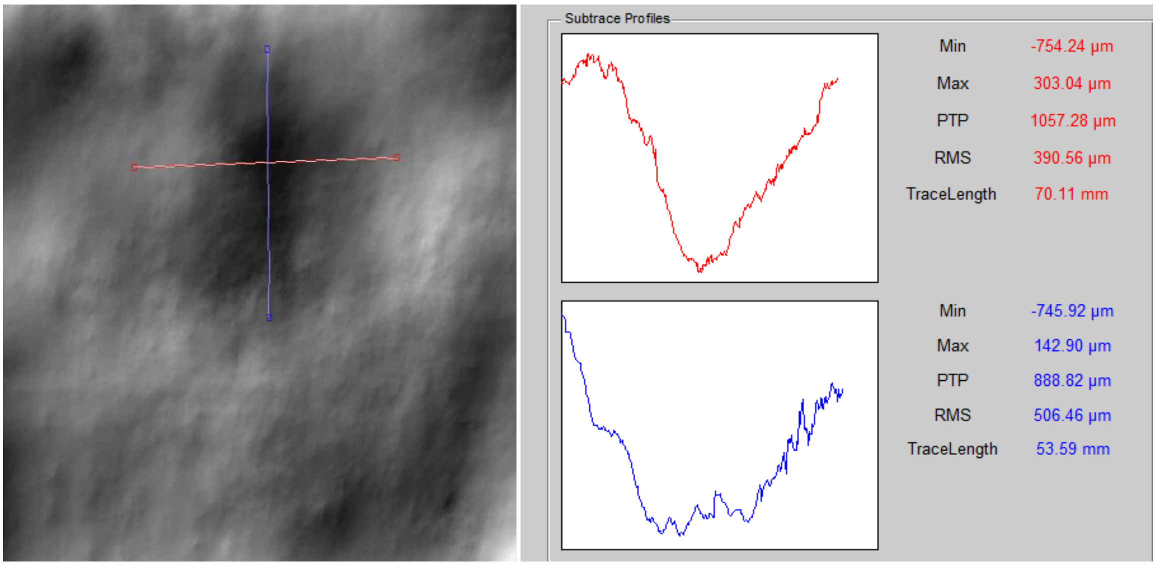


Figure 5.13: 2D image and subtrace details for a grey metal surface illuminated with blue light for an exposure time of 50000ms.

3D-Image

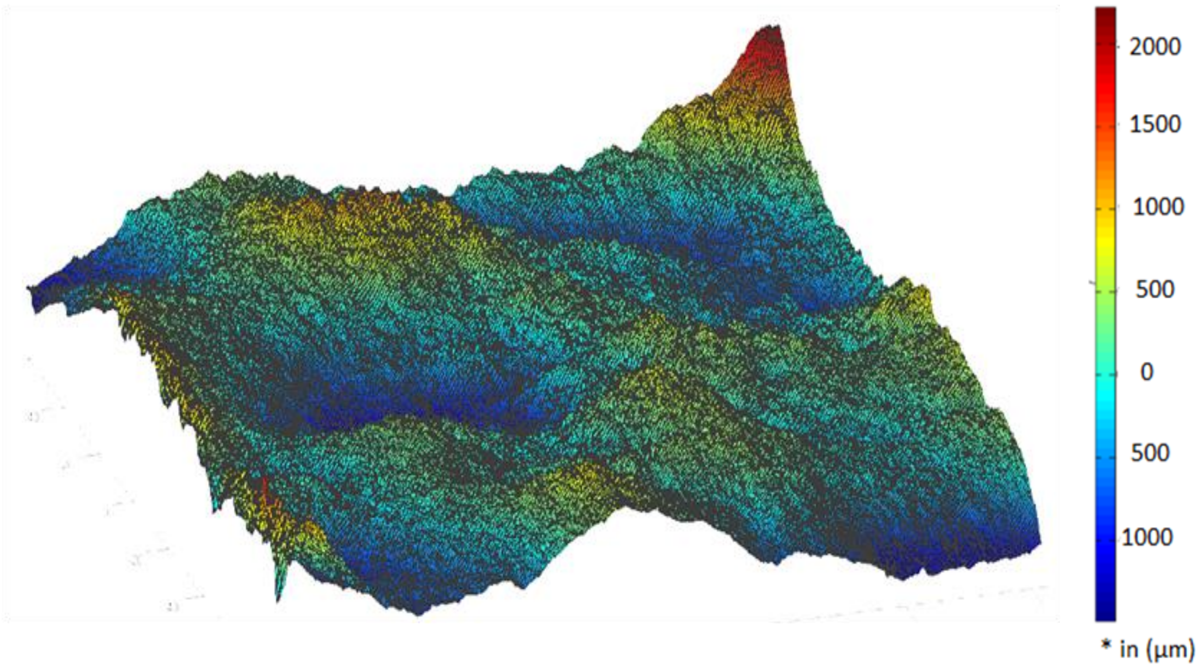


Figure 5.14: 3D image and subtraces details for a grey metal surface illuminated with blue light for an exposure time of 50000ms.

In the grey metal surface illuminated with blue light we examined the area of a hollow. For 15000ms exposure time (blue subtrace) we got 726 μm depth while for 50000μm we got 745μm which in which example the differences are small. We can also see the 3D image of both measurements. In this case the metal is not polished and has big scratches which can easily be detected.

5.2.4 White afrolex

White light, Exposure time = 10000ms

Figure 5.15: The white plastic surface.

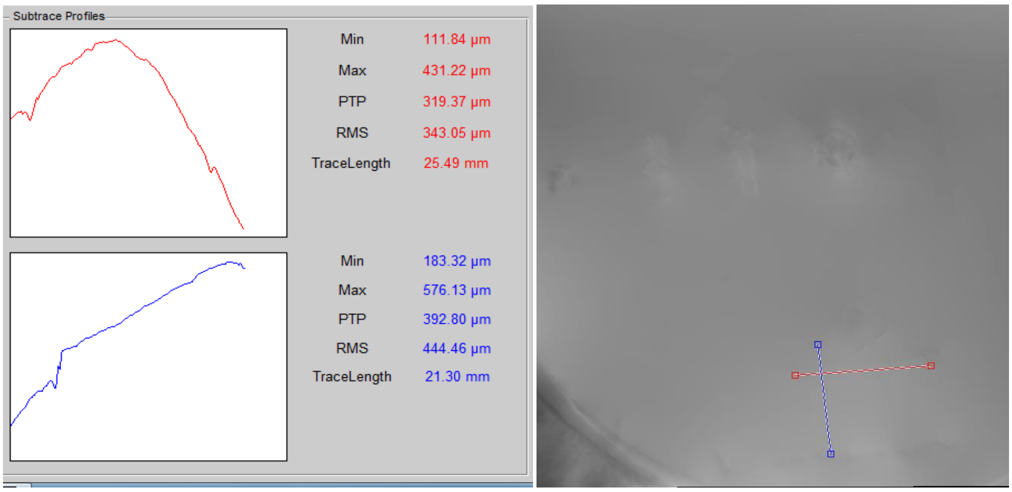


Figure 5.16: 2D image and the subtrace details for a white afrolex surface illuminated with white light for an exposure time of 10000ms.

3D-Image:

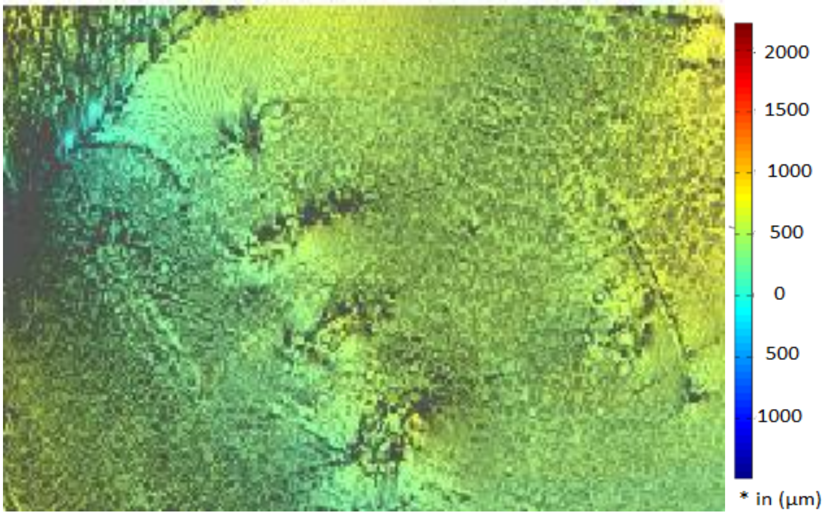


Figure 5.17: 3D image and the subtrace details for a white afrolex surface illuminated with white light for an exposure time of 10000ms.

Exposure time =15000ms

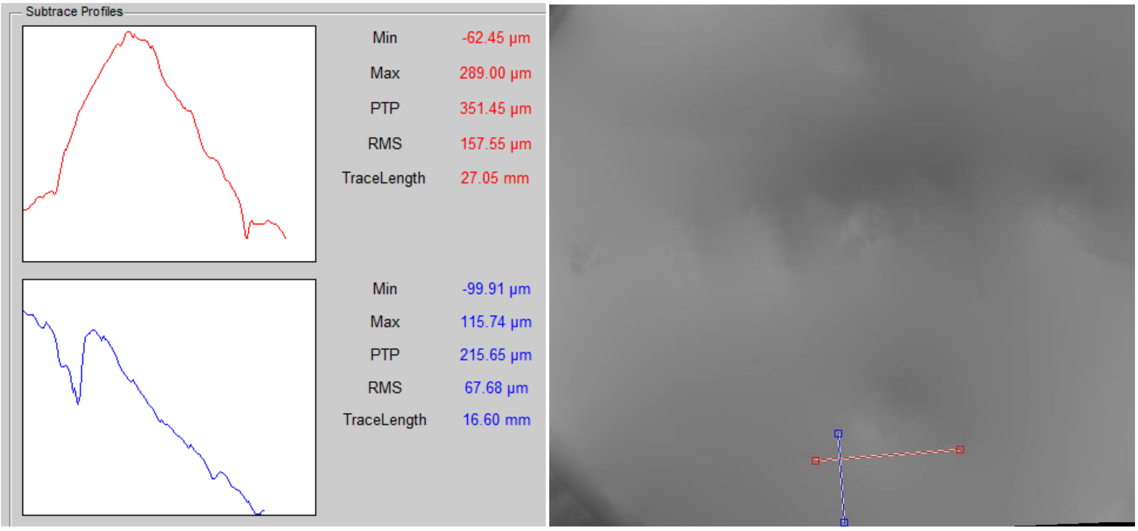


Figure 5.18: 2D image and the subtrace details for a white afrolex surface illuminated with white light for an exposure time of 15000ms.

3D - Image:

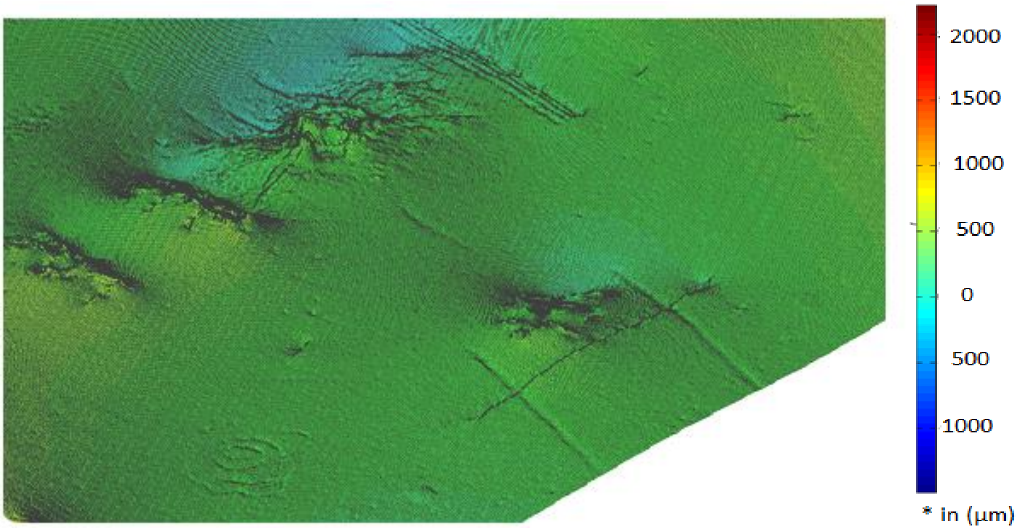


Figure 5.19: 3D image of the white afrolex illuminated with white light for 15000ms exposure time.

The white surfaces are those for which no color is absorbed. In our measurements the area selected gives for 10000ms exposure time a peak of 431µm while for 15000ms exposure time we get a peak of 289µm. In the second case the surface is better illuminated so the irregularities are better detected, 3D representation is also showed above.

5.2.5 Black metal surface

One disadvantage of the black surfaces is that dust can easily be detected on the surface. Strictly speaking, dust particles and particulates are not part of the intrinsic surface roughness. However, unless special care is taken, surfaces are always covered with dust. Dust can be in the form of fine particles of sand or similar hard materials or even very fine particles left from evaporating water vapor or cleaning agents. The size of dust cannot be neglected when the surface has not been cleaned. For this reason, cleaning the surface before the measurement is highly important.

Parameters for Black Metal Surface: White light with 15000ms and 50000ms exposure time.

Exposure time = 15000ms

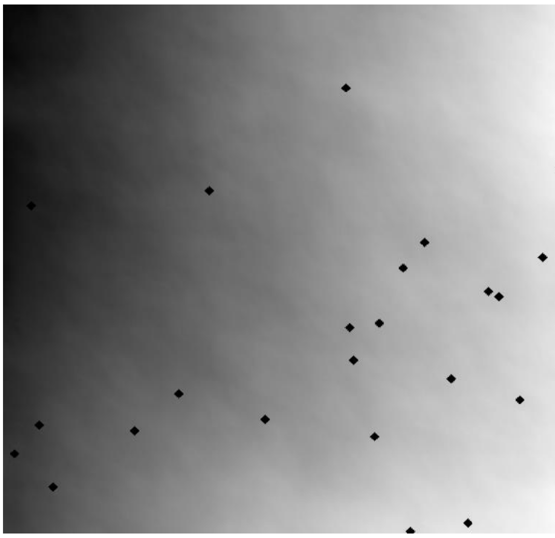


Figure 5.20: Black metal surface illuminated with white light for an exposure time of 15000ms.

Exposure time is 50000ms.

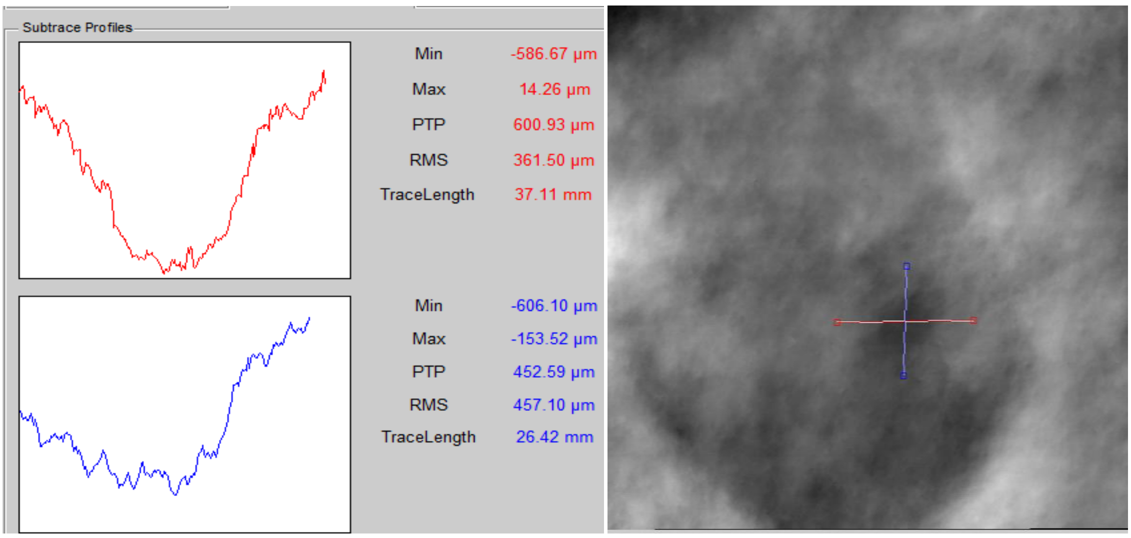


Figure 5.21: Black metal surface illuminated with white light for an exposure time of 50000ms.

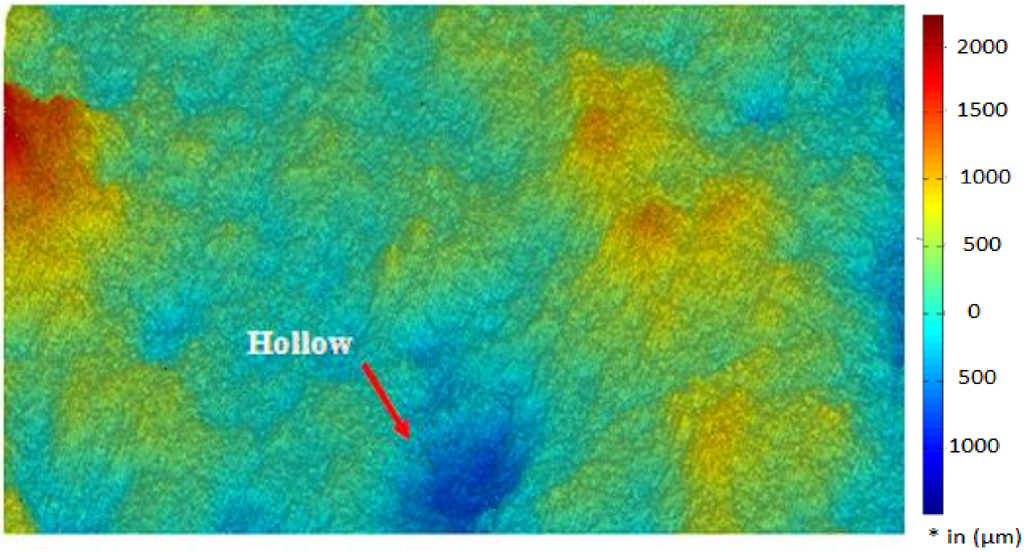


Figure 5.22: 3D image of the black surface illuminated with white light for an exposure time of 50000ms.

One important thing that should be mentioned is that the surfaces should be cleaned before we take the measurements and this can be easily seen from the measurements above showing surface dust particles. Of course our laboratory has dust particles and the surface cannot be perfectly cleaned but at least we keep a satisfying cleaning level on the surface. In the first case with exposure time 15000ms we cannot acquire any surface profile whereas with 50000ms exposure time we get the irregularities in the black surface. This was a problem for the previous WMS system that it was not able to detect the surface profile of black surfaces. With the new system if the surface is properly illuminated we can get the details above.

5.3 Discussion and Results

From the measurements above we can draw some conclusions for the results. Here are some of them.

To start with, the yellow surface when illuminated with white light for the same “hollow “spot gives a depth of 40μm (30000ms exposure time) compared to a 50μm depth (50000ms exposure time). In this case we can observe that the image on the latter measurements is sharper because the surface is better illuminated with 50000ms exposure time. When we change to blue light the image is blurred compared to the white light. In this yellow surface we can detect irregularities with 791μm height and 749μm depth in different positions for 15000ms exposure time. Blue light in this case doesn’t detect as small imperfections as with the white light.

The orange surface was illuminated with white light and we examined the same spot and we got 144μm depth for 10000ms exposure time and 190μm for 50000ms.What we see is that in the second case the image is more clear and the hollow is slightly better detected. Moreover, we next applied green light to the surface and we got 1.8mm depth for 10000ms exposure time and 0.5mm for 150000ms. With this color-wavelength we can understand that when the sample is better illuminated smaller details are detected.

The white afrolex illuminated with white light for the same area of evaluation gives a height of 432μm with 10000ms exposure time while the same subtrace gives 289μm for 15000ms. The details are better again demonstrated for the longer exposure time.

When the metal sheet is illuminated with blue light we get 733μm and 754μm for 15000ms and 50000ms respectively. We can observe that the differences in this case are small. Not to forget that the surface is unpolished.

The black surface induces some problems both in the new WMS and in the old. During shorter exposure times, the surface have many black spots which might be from dust particles that are detected in the surface. When we increase the exposure to 50000ms, surface profile of 586μm depth.

From the measurements above, many conclusions can be drawn. Measurements results vary according to surfaces, light color, exposure time and position within the sample. What we observe is that when the surface is sufficiently illuminated then the surface profile and irregularities can easily been detected.

5.4 Advantages and Disadvantages

Advantages

The new WMS system has many advantages which took the initial idea one step ahead; some of these reasons are outlined in the next. First of all, with the old WMS the Black box’s commands were difficult to understand and it was impossible to change its factory parameters, so we replaced it with a DMX USB interface. The delays for sending and receiving the commands from the Blackbox which made our system very slow have been removed and replaced by a DMX-USB box. Moreover, the biggest disadvantage of the old WMS was that the radiant flux of every flash light was different so energy sensors were used to measure the different radiant intensities and then normalize them. But with the new system the RGB LED lights have the same intensity and no energy normalization is needed. Furthermore, the RGB lights are more homogenous at the radiated surface, the beam angle is near 60^0, they have longer lifetime, they are cheap and can easily be found in the market.

In the old system the evaluated surface was giving blurred images when larger samples (in height and width) were placed, this is because the flash lights were positioned in lower heights so they could not illuminate the whole area of the sample. In the new system more LED lights are used (32 lamps) in order to cover a large area of evaluation and the above problem was slightly improved. What is more, one advantage of the new WMS system is that the RGB COB LED panels can easily be tilted compared to the old flash lights system in which lights were fixed and already calibrated, making it difficult to adjust or change the angle of light sources.

As regards the Labview, a goal for the previous system was to adjust/initialize the camera only once and then loop through, start and stop the acquisition. In the new LabView this was achieved. Now the system sets the camera parameters once and the runs/stops. In the old LabView same VI’s were used many times consuming a lot of time and space. In the new Labview we use less space to run the system and the programming is easy to follow and understand.

Apart from the reasons above in our WMS system we can measure painted and unpainted surfaces without changing the setting/parameters of the system. One main advantage of WMS compared for example with the D-sight technique is that in our system the surface needs no preparation like putting fluid film of water or oil.

In our new LED lights the spectrum includes three main wavelengths that can be used separately each time in our measurements to improve the amount of reflected radiant intensity from the sample in the camera field of view. One more advantage is that we can determine surface defects on two colored surfaces. Because the differences in the image intensity can occur for example from shadowing effects on irregularities, the 3D-shape of the object, or from the object’s paints. For example if we have a red surface with green points and we illuminate the surface with red color the green points will appear as a black spots(irregularity) in the grayscale image. If now we illuminate the surface with green light there are no point defects. So in this case with respective image processing, irregularities could be distinguished from difference in colors in the surface

Disadvantages

A problem of both the old and the new project is that exposure time has to be adjusted and inserted manually before running the system depending on the illuminated surface so as to have satisfying results without being too dark or saturated. One drawback for the old system was that there was a limitation in the exposure time (around 3400μs) after being tested due to the fact that energy sensors were fully saturated there. In the new RGB COB Led lights there is not such limitation.

For measuring bigger areas than $27x27cm^2$ the focal length of the camera has to be adjusted. Matlab codes and the evaluation are complicated in its writing and new Matlab evaluation system could be developed by engineers together with programmers to make it faster.

Chapter 6

6.1 Comparisons of two projects

The old WMS system was a good start for surface roughness evaluation but we faced problems that should have been changed. First of all, the flash lights were not so easy to control and were limiting our possibilities of testing. Moreover, with the flash light we could only use white light which was a hinder in the case we wanted to measure surfaces with different color source in order to detect imperfections. This is the first advantage of the new RBG LED panels. Not only is easy to programme and communicate with the new lights but also changes can be done so fast and colors can be selected from the front panel of LabView with a click of the mouse.

Second improvement of the new WMS system is the removal of energy sensors. In the old project energies were normalized for each flash light though these energy sensors (one for each module) and their values were sent to the Blackbox in order to transfer them to the computer. In the new WMS system LED lights have stable energy flux which are saved in the energy files and are not changed during the running of the system. No calibration or normalization is needed.

The initial plan was to replace the Blackbox with a new interface to communicate with the lights using easily comprehended commands for all users both for saving time and system efficiency. The Blackbox helped to synchronize flashlights with the camera, read energy sensors and provide WMS power connection. The above functions were accomplished with many connections and wirings as well as long commands of programming. The DMX-USB512 bus made the above functions easier, faster and more comprehensive for the user. The communication now is based on the DMX protocol which is widely used for programming lights, sounds and video performances. The new WMS project is mostly based on the DMX interface which in turn is upgraded by new RGB LED lights.

The hardware part is of high importance for improving our WMS system but wouldn’t have the satisfying results if is not supported by changing the Labview and Matlab programme. The numbers of the lamps now are 32 compared to 20 in the old system which means that we have more data to evaluate and the accuracy of our results is now improved. We get 32 different heights images so irregularities are now better tested.

A new LabView programme was made using the DMX protocol and the choice of selecting the color and the number of lamps that are going to be used before running the system. One big advantage of the new WMS system is that it runs in less than 9s which is half the time of the old project with 19s.Furthermore Matlab Evaluation application was adjusted to the new parameters (system coordinates) and number of LED lights (32lamps).

For the above reasons we can observe that the new WMS system is improved and operates better than the previous one in different levels.

6.2 Other surface roughness techniques

1) ABIS (Automated Body Inspection System) is a system to automatically check car-bodies on the production line for dents and ripples. It is designed in collaboration of the AUDI AG Ingolstadt. Two components are integrated into the production line: a sensor portal with range sensors that scan the whole surface of the body and a portal with robots that mark regions with detected defects (see Figure 6.1). The processing chain covers the following tasks: 1) the camera and robot positions are individually adapted to the type of car body that enters the sensor portal (only those car types are checked). 2) Data acquisition(20-25 range sensors scan the body surface,400-600images are taken, due to vibrations of the production line, each range image is evaluated by spatial phase shift from a single sinusoidal fringe pattern that is projected by a flash light). 3) Defect analysis and classification (the CBR algorithm decides whether the candidate is class A or B. 5) Marking system (according to the classification the corresponding regions are painted by robots and polished manually).

2) Nissan Motor Corp. introduced a system which illuminated the surface by a laser line and a linear CCD array detects distortions of the reflected line which are caused by local curvature.

3) Sira Ltd. U.K., Siemens AG Germany and Diffracto Ltd Canada use a retroreflective screen to reflect the light back towards its source. The sensor is placed near to the light source and observes the retroreflected light. Intensity variations due to local slope variations are amplified by the imperfection of the retroreflector. The Sira system scans the surface pointwise. Siemens and Diffracto use CCD cameras to directly acquire 2-d images, which are special kinds of derivatives of the surface geometry. The Diffracto system is commercialized with the trademark D sight. Since the previous methods do not acquire any geometrical data they are suitable for qualitative measurements only. Thus, they are mainly used to visualize defects. Beyond this they require reflective surfaces. Unpainted car-bodies must be coated with a fluid of water or oil in advance. [7]

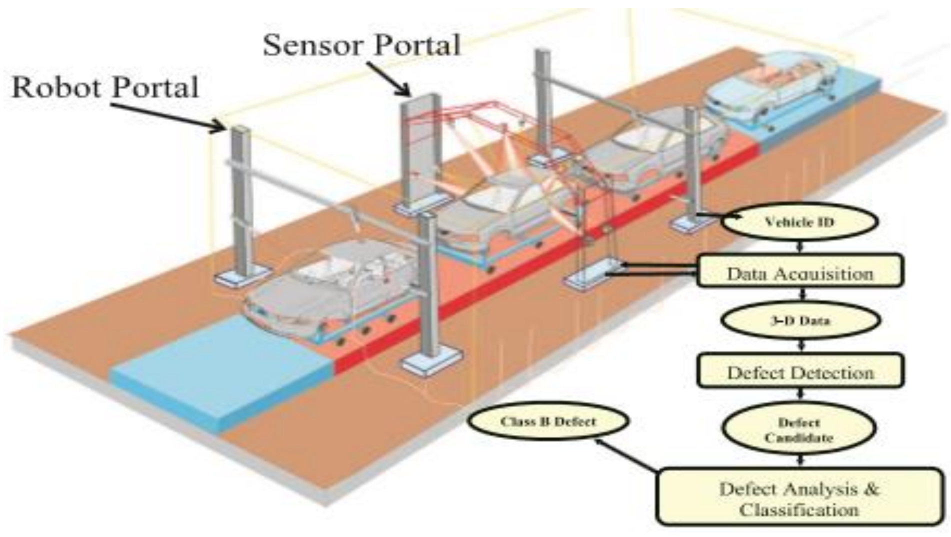


Figure 6.1: Integration of ABIS into the production line

4) The most common instrument for assessing surface characteristics is based on stylus measurement systems. One drawback of this technique is that there is surface damage even if the force has been reduced to 1-10Mn. Compared to the WMS; stylus technique needs a lot of time to generate the data. They scan the surface point wise which leads to a typical measurement time of over half an hour for a measurement are of 600 mm x 600 mm depending on the amount of measurement points.

5) Microscopy is usually used for surface measurement in a limited range of micro and nano scales. In the measurement of 3D surface topography, surface roughness and surface defects, the typical microscopes are scanning tunneling microscopy (STM), atomic force microscopy (AFM), Optical microscopy (OM), and differential interference contract microscopy (DIC).

6) The successful interferometric measurement techniques in surface topography are phase stepping interferometry (PSI), vertical scanning interferometry (VSI), the PSI has the highest accuracy which can reach $\lambda/100$, where λ is the wavelength of the used light. In contrast, the applications of the conventional optical inteferometries are generally limited by the wave length of visible light. This is because the resolution of optical interferometry is restricted to half the wavelength of the used light. Furthermore, the surface area measured by optical interferometric instruments is also small. The surface areas measured are often in the millimeter range.

6.3 Improvements

Improvements set in the previous WMS system and are now completed:

- Simplify the system by replacing some parts (e.g. Blackbox/Modules). We replaced the Blackbox with a DMX-USB interface and the flash lights are now replaced by RGB COB LED lights.
- Energy values are now stable for all LED lights compared to the old WMS system when the energy values had always to be normalized and controlled.
- Labview now is easier to understand and takes less space. Time has been speeded up. The old WMS was running for 19s while the new one is only 9s.
- The new LED panels with 32lamps give us more information for the sample than the old system with 20images.
- In the new system we can select colors (Red, Green, and Blue) in our LED lights compared to the old system where only white light was used.

Future Improvements

Tasks that may be done in the future could be:

Image Acquisition

- Develop a system to get automatically the right exposure time.
- Add a help for sample placement. Due to darkness inside the black room, light is needed to adjust the evaluated surface exactly in the middle of the table. This light comes from a gooseneck lamp which is manually turned on/ off every time before the system starts. One future work will be to mount a lamp inside the dark room and to automatically control it using LabView.
- Change the camera lens to get a higher resolution .To get a bigger or smaller measuring area/pixel size, another lens has to be mounted. (Smaller measuring area means smaller pixel size and then we will have the ability to measure finer structures and defects).

Image Processing:

- Continue the attempt of the second MATLAB program.
- Add more functions for surface analysis (e.g. median filtering for reducing noise).
- Find a way to export the evaluated surface topography to MountainsMap.
- Continue the attempt of the second MATLAB program.
- In Matlab evaluation application one future improvement will be to set x- y axis (ruler) on the 2d image so as to make the trace line even more precise when it comes to compare it with next measurements. In the recent system subtraces are set according to human perception making the results and comparisons not completely accurate.
- Speed up the Matlab evaluation (better programming – more efficient computer).

Chapter 7

7.1 Conclusions

The new Waviness Measurement system has made a step forward and as mentioned above there are many advantages why the improved version demonstrates better results. First of all, the biggest drawback for the old WMS was the “black box” which was difficult to comprehend, it was time consuming and difficult to change its parameters. This was replaced by a DMX-USB bus which made the communication with the lights easier, faster and more efficient. In general our existing devices are easily found in the market in contrary to the Blackbox or flash lights.
Apart from the Blackbox the radiant flux of the flash lights was normalized and calibrated in every measurement which made our system slower. For this reason the flash lights were replaced by RBG COB LED panels. RGB lights have the same energy values and no calibration or sensor is needed. Lights have a better beam angle (60^0), communicate faster with our computer and are easily programmed. Not only the new panels make our system faster but also they can illuminate the surface with different colors in case we want to evaluate surfaces with different colors on it. Last but not least, with the new RGB panels the tilting can easily be changed and adjusted compared to the flashing lights which were fixed in the setup.
As regards the LabView, the system now is programmed and automated in 9s compared to the old WMS which was programmed in 19s for a measurement with 50000ms exposure time. The visual programming takes less space and parameters like color, intensity and exposure time are all set in the front panel. The camera parameters are set once and then the system takes measurements without setting these parameters again. Labview acquires 32images and saves it the Matlab images folder. As the Labview runs we can see the images grabbed in the front panel.
After the image acquisition we use Matlab to evaluate the images. Energy values have already been adjusted to the new RGB LED lights for white light. The Matlab has been adjusted to run with 8leds in each corner and the system coordinates are already introduced in the code. The evaluation takes 2-5minutes according to the selected area. This is quite reasonable as more data are being calculated in the new 32led system.
In the Black metal surface the surface had not satisfying results compared to other color surfaces. The surface profile was detected in higher exposure times because the surface was better illuminated. On the other hand, the colored surfaces demonstrated better irregularities in white and blue light because the camera quantum efficiency is shifted to white-blue wavelengths. In the yellow metal surface we can detect 40µm hollow with 30000ms exposure time compared to 50µm hollow with 50000ms exposure time When it has to do with unpolished

surfaces imperfections are more distinctive like 733μm depth for a hollow for 15000ms exposure time in a 34mm trace length. The WMS can detect irregularities in both painted and unpainted surfaces and this is one of the advantages of this system compared to other techniques (e.g. D-sight technique).

7.2 Outlook

The new WMS system now has been improved. Changes in set up and software had to be made. For this reason, flash lights were replaced by RGB COB LED lights and a new DMX interface was used instead of the Blackbox. The general structure and setup of the WMS has not changed. Camera parameters are the same. The table stands in the middle of the room (3 x 3 x 2.2 meters) and the black anti reflection shield is placed. One future improvement for the setup would be a lamp which will help to illuminate the sample in the darkroom without using the gooseneck lamp and also inserted into LabView before the system runs.
Both LabView and Matlab had to be reprogrammed with the new parameters and settings. A big advantage of the new LabView programme is that runs faster and the parameters can easily change.
As we already know the surface of evaluation is 27x27 cm^2 with high resolution in z-direction 5-50μm. The existing horizontal resolution is 0.2mm but if we want to evaluate areas bigger than $1m^2$ the focal length of the camera lens has to be adjusted.
The measurements were taken on different areas like polished and unpolished metal sheet panels, mechanical tools and plastic surfaces. The exposure time was adjusted to the evaluated area and the color of the light source (The same exposure time demonstrates different image profile from white and red light).In this case comparisons were made in different levels for instance, comparisons within the same sample or comparisons with the same surface with different exposure times and color light.
From the reasons mentioned above, the new WMS system now is easier to understand, operates faster and we get sufficient results which set the basis for this technique to be applied in a the car industry in the near future.

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Appendix:

A. **Specification of camera Basler GigE acA2040-25gm.**

Specification of acA2040-25gm	
Sensor size (H x V pixels)	2048 x 2048
Sensor Types	CMOSIS CMV4000-2E5M Progressive scan CMOS Global shutter
Optical Size	1″
Pixel size	5.5 µm x 5.5µm
Max.Frame Rate (at full resolution)	25fps
Exposure time [µs]	Minimum: 24 Maximum 1000000
Camera gain (raw parameter)	Min setting : 33 Max setting (12 bit depth) : 512
Mono Color	Mono
Data Output Type	Fast Ethernet (100Mbit/s) or Gigabit Ethernet (1000Mbit/s)
Pixel Data Format	Mono 12
ADC Bit Depth	12 bits
Synchronization	Via external trigger signal, via the Ethernet connection or free run
Exposure Control	Via external trigger signal or programmable via the camera API
Camera Power Requirements	PoE (Power over Ethernet 802.3af compliant) or +12VDC (±10%), <1% ripple, supplied via the camera's 6pin Hirose connector ≈ 2.9W when using Power over Ethernet
I/O Ports	1 opto-isolated input line and 1 opto-isolated output line
Lens Adaptor	C-mount
Size (L x W x H)	42.0mm x 29mm (without lens adapter or connectors) 60.3 mm x 29mm (with lens adapter and connectors)
Weight	< 90g
Conformity	CE, UL (in preparation), FCC, GeniCam, GigE, IP30,RoHS,IEEE 802.3af (PoE)
Software Driver	Basler's GigE Vision compliant pylon SDK including filter and performance drivers. Available for Windows and Linux in 32 and 64-bit versions.

B. Specification camera sensor.

Specification CMOSIS CMV4000-2E5M	
Resolution	4MP-2048(H) x 2048(V)
Pixel size	5.5 x 5.5μm^2
Optical Format	1″
Shutter Type	Pipelined global shutter with true CDS
Frame Rate	180fps (10bit) 37 fps (12bit)
Output Interface	16 LVDS outputs @ 480Mbps
Sensitivity	5.56 V/lux.s
Conversion gain	0.075 LSB/e-
Full well charge	13500 e-
Dark noise	13e- (RMS)
Dynamic range	60dB
SNR	Max 41.3 dB
Parasitic light sensitivity	1/50000
Extended dynamic range	Yes , up to 90 dB
Dark current	125 e-/s (25 degC)
Fixed pattern noise	< 1 LSB (<0.1% of full swing)
Chroma	Mono
Supply voltage	1.8V
Power	600mV
Operating temperature range	-30 to +70degC
RoHS compliance	Yes
Package	95pins uPGA

C. Specification camera lens.

Specification NMV-35M1	
Back Focal Length	16.5
EFL (mm)	35
Field Angle 1/ 2 (HxV) :	10.5 x 7.8
Field Angle 1 (H x V):	20.9 x 15.8
Field Angle 2 / 3 (H x V):	14.4 x 10.8
Filter diameter :	Ø35.5 P=0.5
Focus control :	Manual
Focusing range from front of lens (m) :	0.3- inf.
Format :	1″ Megapixel
F-stop	1.4-16
Iris control	Manual
Mount	C
Object Area at M.O.D. (HxV) 1 :	110h x 82v
Object Area at M.O.D. (HxV) 1 / 2 :	54h x 41v
Object Area at M.O.D. (HxV) 2 / 3 :	75h x 56v
Iris Control:	Manual
Object Area at M.O.D. (HxV) 1 :	110h x 82v
Object Area at M.O.D. (HxV) 1 / 2 :	54h x 41v
Object Area at M.O.D. (HxV) 2 / 3 :	75h x 56v
Angle (1″) : Vertical -Horizontal -Diagonal	15.5 deg - 20.9 deg - 26.1 deg

Figures:

Equations:

Tables:

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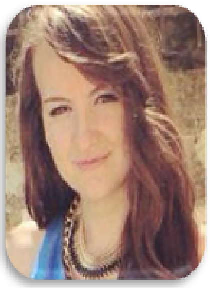

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