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Chromatic depth encoded microscopy for 3D surface measurement

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Abstract This study investigates the integration of chromatic confocal microscopy with a tuneable light source for advanced 3D surface metrology. The objective was to design and evaluate an optical setup capable of performing chromatic depth encoding, followed by 3D data reconstruction. A chromatic confocal microscope is a type of confocal microscope that includes an optical component which add longitudinal chromatic aberration. With this we can determine the height of the sample. In our experimental setup we achieved a precision of 0.51µm and 1.22µm in accuracy using a 5x/0.15NA objective. In a second part of this study, we designed a tuneable light source, capable of generating inputs with arbitrary spectra, in a versatile manner. The tuneable light source is based on a micromirror device (DMD) which can generate custom spectral patterns. The aim is that, such tuneable light source can be used in our chromatic confocal microscope to perform the required wavelength scan without requiring any spectrometer. The study concludes that the obtained results are promising whereas the selected equipment based on a LED, there is no sufficient light for combining the tuneable light source with the chromatic confocal microscope.

Keywords: Chromatic Confocal, 3D microscopy, Focus Variation, Digital Micromirror Device

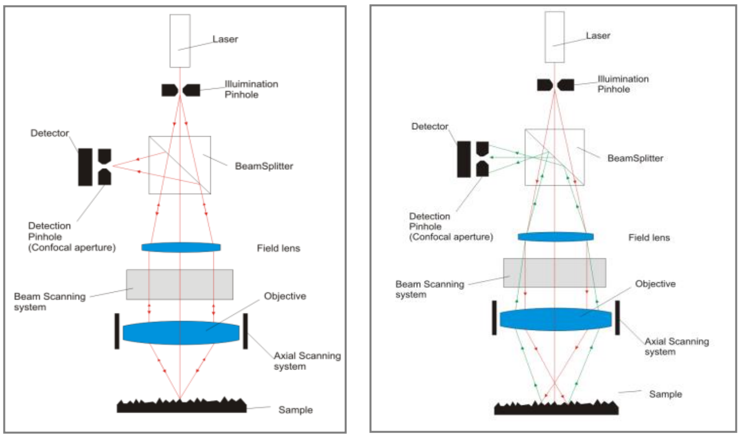
1. Introduction

Nowadays, various surface metrology techniques are available. Depending on how we want to measure we will have the contact techniques and the no-contact ones. The contact methods, such as the Stylus contact profiler, in which a sharp stylus is moved horizontally over the sample surface, by touching it the stylus can know the height of that exact point, another example could be the Coordinate measuring machines, which measure the geometry of physical objects. However, contact techniques can damage or even destroy the measured sample, making them suitable only for large samples or for those where it does not matter if they are destroyed. If we do not want to damage our sample, the non-contact techniques are the desired ones. These techniques are non-contact, non-invasive and faster techniques that the contact ones. We can use light to measure different samples. Depending on the measurement requirements, single-point techniques like triangulation, confocal techniques, or interferometry can be used. If imaging is needed, techniques such as fringe projection, holography, confocal, or interferometry are available. In this study, we focus on the confocal microscopy technique.

1.1. Confocal microscopy technique

Invented in 1975, confocal microscopy did not become practical until computers gained sufficient processing power. Its primary application is in biological studies and obtaining 3D reconstructions of specimens, which requires an axial scan. A confocal microscope produces optically sectioned images of the sample under inspection. According to Artigas. R, this optical sectioning is achieved by restricting the illuminated regions on the sample using a structured illumination pattern and recovering the reflected light with a second pattern identical to the illumination one. This pattern can be a simple pinhole placed on the optical axis, a set of pinholes, a slit, or any other configuration that effectively reduces the size of the illuminated and detected regions, by restricting the light we are creating an optical sectioning which enables surface metrology. In this study, we use a single pinhole to restrict the illuminated area. Figure 1 illustrates the working principle of a confocal microscope, showing the sample in focus and out of focus.

When the surface is exactly on the focal plane of the objective (figure 1a), the reflected light is imaged onto the confocal aperture, resulting in a high recorded signal. Conversely, when the surface is out of the focal plane of the objective (figure 1b), the recorded signal is lower because the reflected light is blocked by the confocal aperture.



(a) (b)

Figure 1. Basic setup of a Laser Scanning Microscope: (a) sample on focus, (b) sample out of focus.

Chromatic aberration is a common optical phenomenon that occurs when a lens cannot bring all different wavelengths of light to a single converging point, causing the various wavelengths to focus on different planes. We can leverage this phenomenon by combining it with the confocal technique to create a chromatic confocal microscope.

To achieve chromaticity, various optical elements can be employed to simplify the process, as for example Fresnel lens or prisms. In contrast, doublets are lenses specifically designed to minimize chromatic aberration by combining two types of glass with different dispersion properties, effectively cancelling out the chromaticity. However, singlet lenses, which are single-element lenses, do exhibit chromatic aberration because they cannot bring all wavelengths of light to a single focal point, this is called longitudinal chromaticity, because the variation on the focus is due to the refractive index. This dispersion creates a range of focal points for different wavelengths, visualized as a spread of colors along the optical axis, when the chromaticity is high, we obtain more range to measure, that means that the difference from blue to red is bigger. But if we want higher precision, we will need less range, so less chromaticity range. The difference between a doublet and a singlet is shown in figure 2.

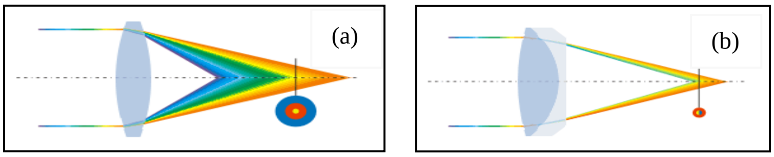


Figure 2. Chromatic dispersion: (a) singlet with chromatic aberration, (b) doublet with less chromatic aberration.

1.2. Chromatic confocal microscopy technique

Chromatic confocal microscopy is a measuring technique that combines a chromatic confocal probe with a lateral scanning system. It's measuring principle is the same as the single-point confocal configuration, we need to restrict light, to create an optical sectioning. But in the chromatic confocal the light that is reflected from the sample passes now through a dispersive lens (figure 2) before arriving to the second pinhole. Depending on the position of the sample, only one wavelength will be in focus. This focused light goes through the second pinhole and is captured by a spectrometer, which detects the exact wavelength that is in focus. So, this chromatic probe enables us scanning in the z plane, while in a confocal configuration this z-scan is needed. When we desire to measure all the sample, we will need to make lateral scan in the x and y axes. As Blateyron. F mention, to have a chromatic confocal, we will need that the optical path from the light source to the workpiece surface has to be equal to the optical path from the workpiece to the detector. This single-point measuring technique is insensitive to ambient light and does not require an axial scan, as the chromaticity handles that function. Figure 3 illustrates a basic chromatic confocal setup.

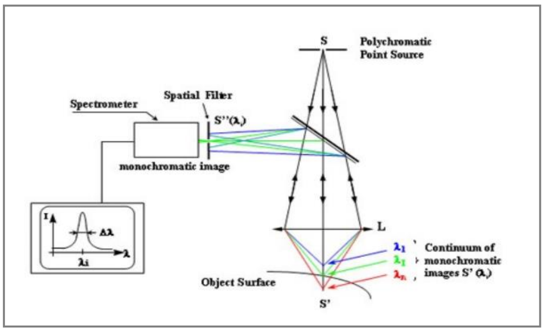


Figure 3. Basic setup of a Chromatic confocal microscope

When the focal point is above or below the surface, so it is out of focus, the reflected light do not pass through the second PH, and the detected intensity in the spectrometer is zero. When the focal point lies exactly on the surface, the detected intensity for that wavelength is maximum.
As we have optical section capacity, we can make a scan to find this exact focus for each point of the sample, this scan is known as axial response (figure 4). F Blateyron stated that the detected intensity needs to be within two limits. If there is insufficient light, it will not be detected above the noise level. Conversely, if there is too much light, the detector can saturate, resulting in erroneous peaks. Blateyron also identified various non-measured points; for instance, when the surface is higher or lower than the vertical limit of measurement. This issue can be resolved by adjusting the z-axis. However, if the focus falls into a hole, there is no solution, and this point becomes an outlier.

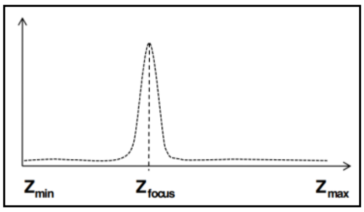


Figure 4. Axial response of a confocal and chromatic confocal microscope, z in µm.

The objective of this study is to design an optical setup capable of achieving chromatic depth encoding for a microscope on a benchtop table. This setup aims to perform optical sectioning and acquire resulting images, followed by 3D data reconstruction through image processing using Python. Additionally, the study includes an analysis of the system's performance, characteristics, and calibration process. In addition, a tuneable light source was designed and experimentally demonstrated, and the study explored the possibility of using such light source for effectively performing the wavelength scan, thereby dropping the need to use a spectrometer.

2. Method

2.1. Experimental chromatic confocal setup

The setup depicted in figure 6 shows a confocal microscope combined with a dispersive lens (H). The light goes through the first path (blue arrow), arrive to the sample. The reflected light goes through the second path (pink arrow), thanks to a beam splitter(L).

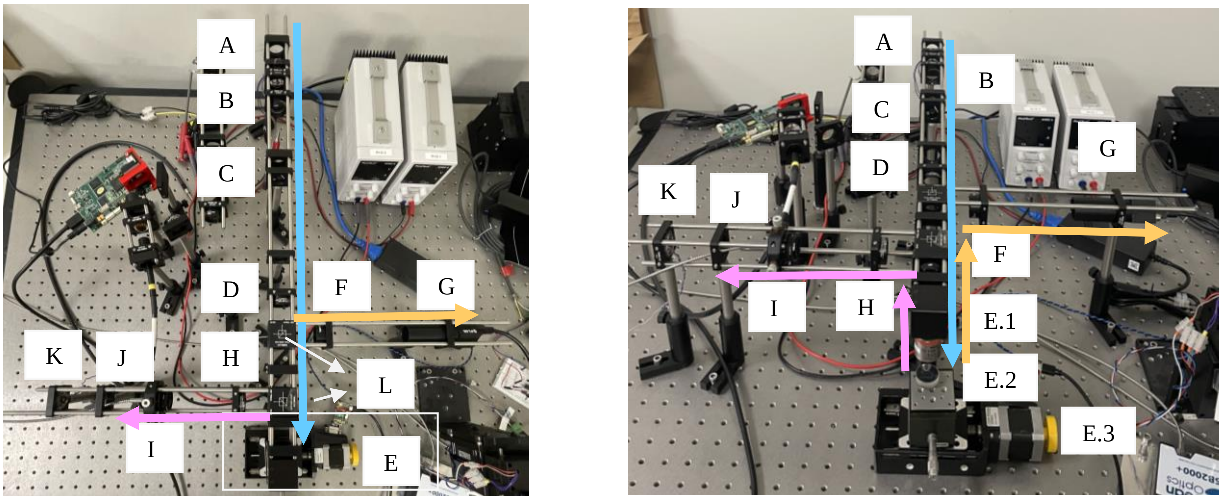
A white LED (A) serves as the light source and with a collimating lens of 16mm focal length, we crate an infinity image of the LED. This image goes through the first lens (B), a doublet with a focal on 150mm, which focuses the LED image onto the first pinhole (C). This image must be projected into the sample, and to do so it need to pass through another doublet of 200mm of focal (D) which prepares the light to enter into the objective, the first pinhole (C) is situated at exactly the focal distance, so when the light passes through the doublet (D), goes out collimated. Now this infinity light goes through a Nikon's 5x objective (E.1) and focuses the light onto the sample (E.2). When le light arrives to the sample the first path (blue arrow) is done.

The reflected light from the sample follows the second path (pink arrow), this reflected light passes again through the objective (E.1), and then though a beam splitter (L), which splits the light into 2, the one that follows the second path arrive to the dispersive lens (H), a singlet of 100mm focal length which, thanks to longitudinal chromaticity, spread the light into the different wavelength. The one that is in focus passes completely through the second pinhole (I) and arrive to an Ocean Optics USB200 Spectrometer (J).

In the chromatic confocal configuration, we have a dependence between the wavelength and the focal plane as mentioned in section 1.2, so depending on the position of the sample (E.2), we will obtain one wavelength or another in the spectrometer (J), thanks to the dispersive lens (H).

In the section E we can appreciate a motor (E.3), this motor is used in vertical position or horizontal position (as in figure 6) to scan. To obtain the calibration curve, consisting in measuring the resulting spectra reflected on the mirror, we used the motor in vertical position to scan in z plane and control exactly which is the focal plane, so which wavelength is going to be in focus. To do this we perform a least-squares fit of a parabola in a small region around the maximum signal. Finally, we fit a line model to the dependence of the wavelength with heigh.

We have the third path (yellow arrow), where the light goes through the objective (E.2) and thanks to a beam splitter (L) passes through a doublet (F) of 200mm of focal, and this lens focalized the light into a camera (G), this camara is used to show us the pinholes sizes, were are we measuring, so which sample point are we taking into account to make the measure.



(a) (b)

Figure 6. Experimental set up: (a) chromatic confocal experimental set up from the upper view, (b) chromatic confocal experimental set up from the frontal view. (A) LED + Collimating lens, (B) focusing lens, (C) first pinhole, (D) collimating lens, (E) objective + sample + motor, (E.1) Nikon 5x objective, (E.2) sample, (E.3) motor, (F) focusing lens, (G) camera, (H) singlet lens, (I) second PH, (J) Oceans Optics spectrometer, (K) red LED, (L) beams splitter, (blue arrow) first optical path, (pink arrow) second optical path, (yellow arrow) third optical path.

Also, the camara is being used to make sure that all the system is well focused. To do so we use an interferometric objective. We illuminate with a red LED (figure 6. K), coming from the second path, and we focalize the sample in the point where the interferometric objective has the focus. This focus is in where fringes appear. Once this is in focus, we readjust the place of the first pinhole (C) to focalize it in the same place. With that we are sure that our system is well focalized, and we avoid possible compensations.

To determine the size of the two PH need to know the Airy Disk produced by our objective lens, formula 1 give us the diameter of the Airy disk, where the numerical aperture (NA) is 0.15 and the designed wavelength is 587.6nm. With formula 1 and knowing the magnification we determine that the second PH need to be a 10µm PH and the first one of 20µm.

$$d_{Airy} = 1.22 \cdot \frac{\lambda}{NA} \qquad (1)$$

2.1. Experimental tuneable source setup

In figure 7 we can appreciate the experimental set up for the tuneable light source; to do so we use a digital Micromirror Device (DMD) (G) which is the core component behind image creation and projection in many modern projectors. We can control which mirrors are on, and which are off and with that we are able to tun the spectra as we want.

The yellow arrow shows us the optical path, we start with a with LED and a collimator lens (A), as in section 2.1. Now we have light that comes from infinity and this light focalise in the slit (C), thanks to a doublet (B) of 100mm focal length. Then with another doublet (D) exactly equal to the first one (B), we collimate the incoming light, which arrive to the diffraction grating (E) which creates an image of the slit which is laterally shifted as a function of the wavelength covering the entire DMD in such a way that each column of micromirrors controls light at particular wavelength. This spread light is focused on the DMD (G), thanks to another doublet (F) of 100mm focal length. When light arrive to the DMD can follow two different paths shown in figure 7b, the blue one is when the mirrors of the DMD are off, that means we do not collect that light, and the pink path is when the mirrors are on, and we collect this light with a 100mm focal length doublet (H), after that the light will find a focusing lens, which is inside the black tube, and focuses the light onto a liquid guide (I). With that we can send different patterns into the DMD and obtain different spectra, so we are able to tun the spectra of the with LED thanks to the DMD.

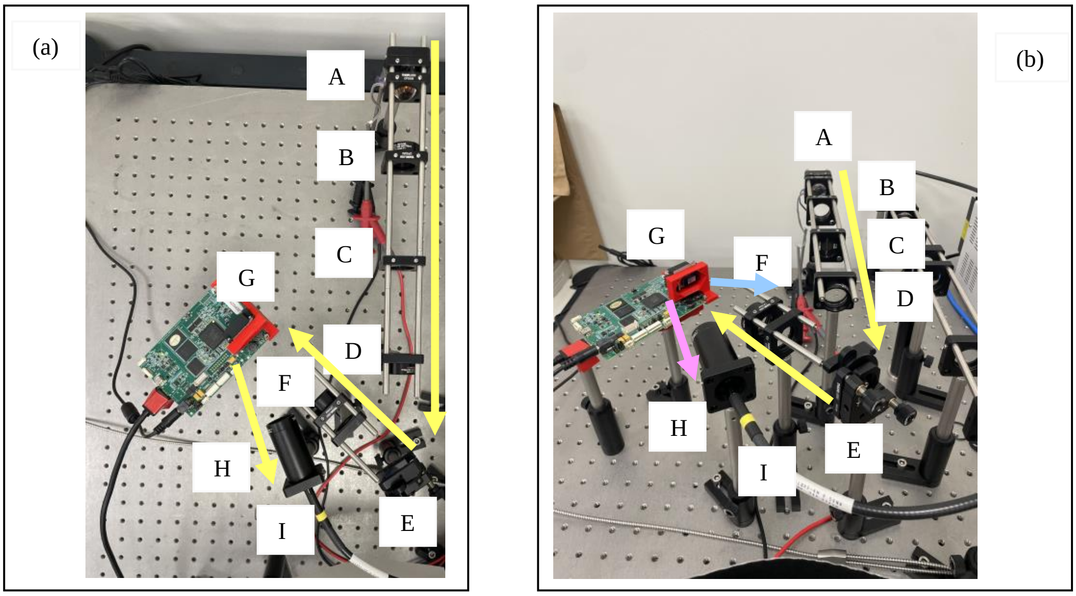


Figure 7. Experimental set up: (a) tuneable source experimental set up from the upper view, (b) tuneable source experimental set up from the frontal view. (A) LED + Collimating lens, (B) focusing lens, (C) slit, (D) collimating lens, (E) diffractive grating, (F) focusing lens, (G) DMD, (H) focusing lens, (I) liquid guide, (yellow arrow) first optical path, (pink arrow) optical path when de DMD is on (blue arrow) optical path when de DMD is of.

3. Results

To obtain all the results we are going to use a flat mirror and a step height of 8µm, but is well known and certificated, and the real value for the steps height is 7.616 ± 0.06µm.

3.1. Chromatic confocal results

In figure 8, we can see the calibration curve obtained. To create this curve, we moved the sample, a mirror, axially by making 10 steps of 10 µm by moving the motor. We took 10 spectra at each step and processed all the information. Finally, we performed a linear regression with the maximum points obtained from the fitted parabolas.

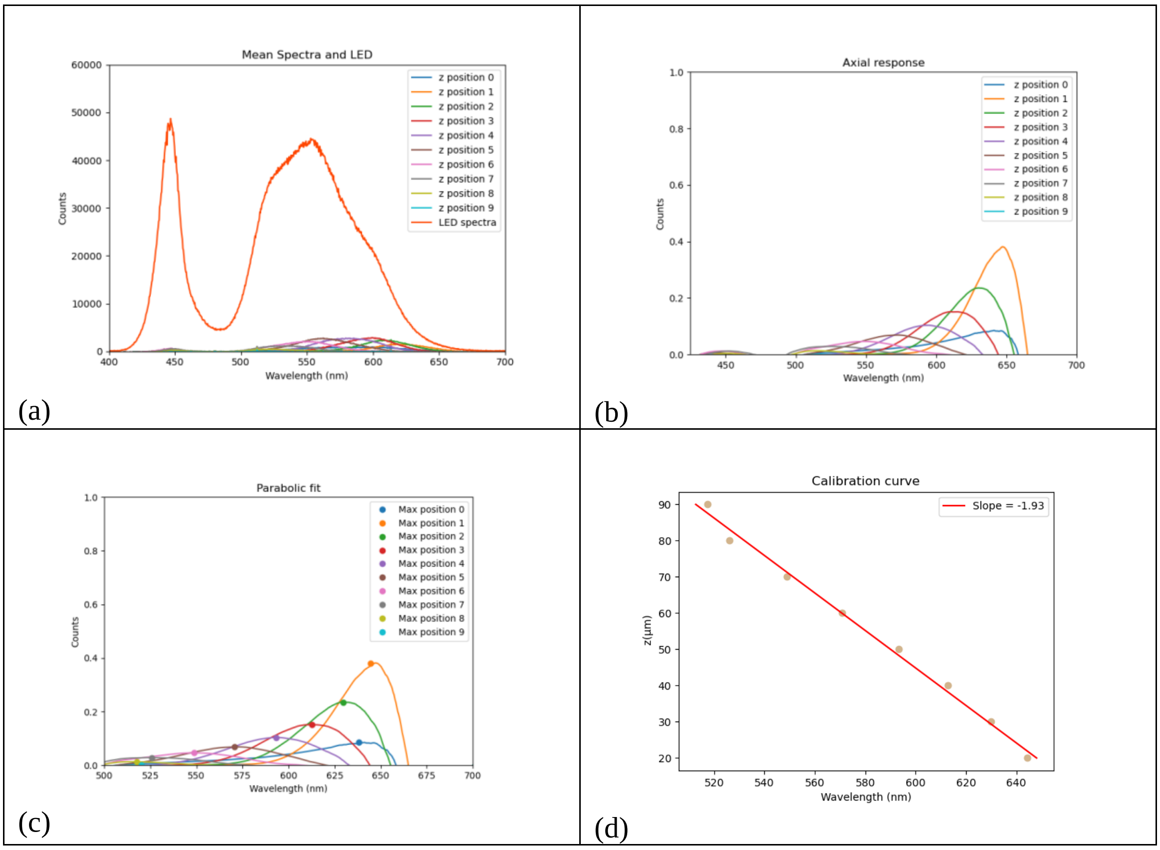


Figure 8. Results obtained from a flat mirror: (a) spectra from the LED and the spectra from the sample, (b) spectra from the sample once the median and smooth filter have been applied, (c) maximum from the parabola fitted, (d) calibration curve of the flat mirror.

Having a good calibration is crucial for obtaining accurate results for different samples. The linear regression fit provides a calibration curve which allows us to determine which height—or z position—corresponds to each wavelength, thus providing information about the 3D profile of our sample. As we mention in section 1.2, it is important that all the measured points are in the measuring range, in our case we can measure 300µm, this is related to the objective used, as more magnification less measuring range.

After obtaining the calibration curve, we evaluate the system's performance using the step height to verify its precision and accuracy. In figure 9, we can see one measurement of the step height of 8µm.

In this case, we move the sample in the x direction by moving the motor in horizontal position (as shown in figure 6) while the z direction is the measurand of our chromatic confocal system.

For this reason, in figure 9(c), we can observe how the peak wavelength changes as the x position changes. To pass from figure 9c to figure 9d we need to apply the calibration curve obtained in figure 8, and to know the step height difference, we take the mean of the absolute values of the points at the lower part of the step height and subtract them from the values at the upper part of the step height. In this instance, the difference is 8.01μm, this result is not as expected but is not far enough, we can estimate an error of 0.8μm.

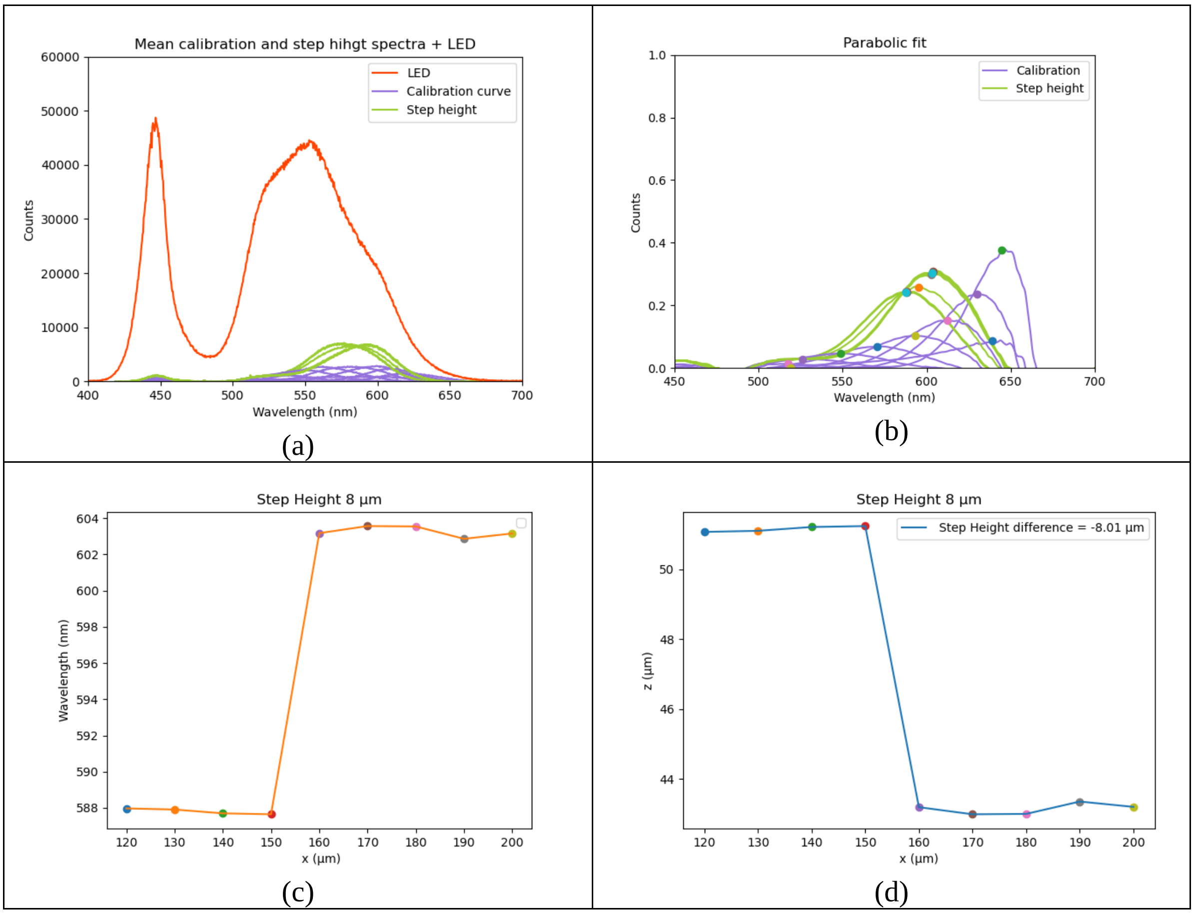


Figure 9. Results obtained from a step height of 8μm: (a) spectra from the LED and the spectra from the flat mirror and the step height, (b) spectra from the sample once the median and smooth filter have been applied and the maximum point localized in the parabola fitting, (c) wavelength that corresponds to each step (d) height of each point measured with the calibration curve

To assess the precision of our experimental setup, we measure 50 points at the lower part of the step and then 50 more points at the upper part. We then calculate the standard deviation for each point, as shown in figure 10.

We can observe that the standard deviation in the lower part and the upper part is very similar—0.24 μm vs. 0.27 μm—as expected. To obtain the standard deviation of the step height we need to consider both values, resulting in a standard deviation, or error, of ±0.51μm.

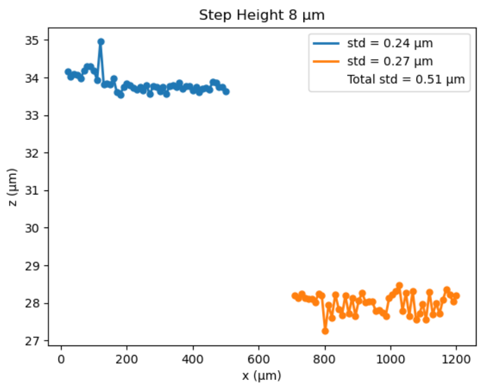


Figure 10. Results for the precision of our experimental setup.

To evaluate the repeatability or accuracy of our experimental setup, we need to substract the known value (7.616 ± 0.06 μm) from the measured one. In table 1 we can appreciate the measured step heights and the differences, and in figure 11 we can appreciate all the measured done, in this case the x position is only for better clarity in the results, all are measuring the same point at different wavelengths, is for that reason that we find the steps at different heights, all are in the measuring range.

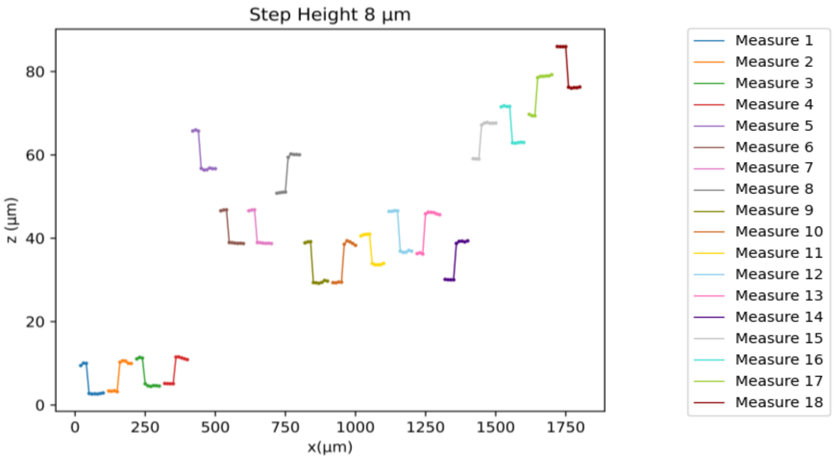


Figure 11. Results for the accuracy of our experimental setup: (a) four different measures of the 8μm step height at different wavelength, (b) four different measures of the 8μm step height at different wavelength, (c) five different measures of the 8μm step height at different wavelength, (d) five different measures of the 8μm step height at different wavelength in the orange one there is an outlier point which is discarded.

Table 1. Results of the step heigh value and the standard deviation of each measure from figure 11.

Measure number	Step height difference(μm)	Standard deviation	Measure number	Step height difference(μm)	Standard deviation
1	7.11	0.55	10	9.43	1.77
2	6.96	0.70	11	7.08	0.58
3	6.59	1.07	12	9.70	2.04
4	6.14	1.52	13	9.65	1.99
5	9.18	1.52	14	9.11	1.45
6	7.89	0.23	15	8.52	0.86
7	7.89	0.23	16	8.70	1.04
8	9.01	1.35	17	9.39	1.73
9	9.58	1.92	18	9.82	2.16
Total standard deviation = 1.22 μm					

We can appreciate that the value of the accuracy is higher than the precision (1.22μm > 0.51μm) it is as expected because in other studies such as "Diffractive lenses for chromatic confocal imaging" the precision and accuracy are litter worse than ours.

3.2. Tuneable source results

As a tuneable source we can send the pattern that we want to the DMD and obtain a completely new and different spectra that do not exist in any current light source. In figure 12(a) we can appreciate two different spectra, one with all the mirrors on (reproducing the emission spectra of the white LED used), and another flat spectrum that we tune to achive a flat spectrum. We achieve this by simply projecting the desired pattern to the DMD. With this setup we achieve great versatility to create arbitrary spectral distributions. So, if we are able to create different spectrums, we can also create some pattern that allows us to make a scanning by having different peaks, in figure 12(b) we can see how a discrete spectrum can be obtained.

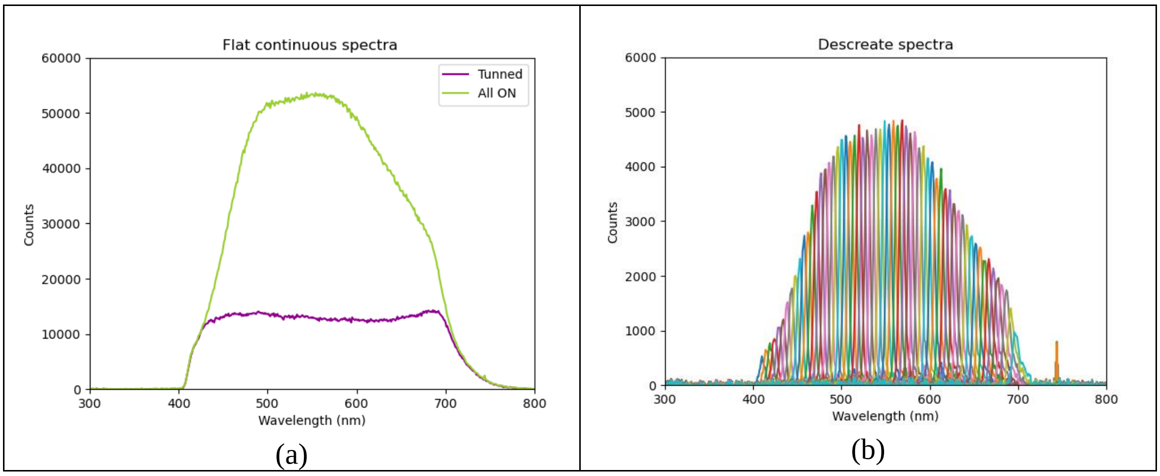


Figure 12. Results obtained sending different patterns to the DMD: (a) in green we can appreciate the spectrum when all the mirrors are ON and in purple, we can appreciate the tunned spectra where we obtain a flat spectrum, (b) discrete spectra obtained by sending patterns of a line to make a scan.

If now we think in making a scanning we need to use the discrete spectrum, but still this spectrum can be tuned, for example we can create a flat spectrum of the discrete one as shown in figure 13(a), or we can even create an ascendent spectra as shown in figure 13(b).

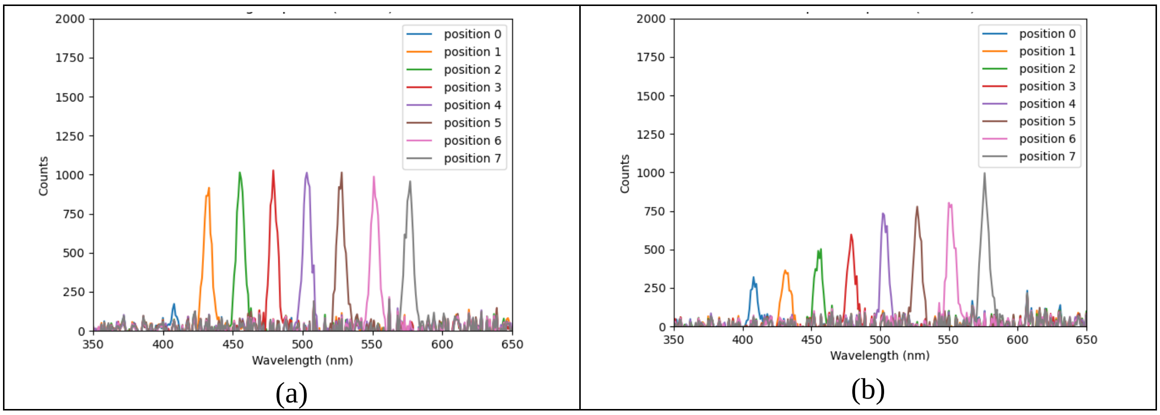


Figure 13. Results obtained sending different patterns to the DMD: (a) flat spectra of a discreate pattern, (b) ascendent spectra of a discreate pattern.

4. Discussion

The results obtained for the chromatic confocal microscope shows us that we have a working system with a precision of 0.51µm and an accuracy of 1.22µm. But obtaining the sufficient amount f light was challenging, because we have a initial PH in which we have a big lose of light, and before arriving at the spectrometer we have 2 beams splitters for the first path and one more for the second path, that means that we lose 3 times the light that comes from the first PH. We used a LED to illuminate both systems, and for the chromatic confocal is not the best source to use, because it does not have a wide spectrum, and in the blue range the intensity was very small, and the detection was very hard. The PH alignment was complicated to, for that reason we add a camera, and it makes the alignment easier. In the future we can change the dispersive lens for a Fresnel lens where the different focuses are more differentiated and that could give us a much better precision and accuracy.

The alignment of the tuneable source was hard, because the required angles need to be very precise, and the challenge was to avoid cropping the light that arrive to the DMD with the different optical elements after the diffraction grating. We could use the tuneable light source to send this tuned light to the chromatic confocal configuration, and with sending only one pattern we could be able to detect one wavelength. Moreover, we can change the spectrometer for a photodetector and detect only if there is or not is. But with our system there is a big loses of light and at the end we could not detect any signal into the spectrometer, one probable solution is to compress both systems, with lenses with shorter focal lengths, and has a more powerful light source. That's because of the just mentioned loose of light in the chromatic confocal, but in the tuneable light source we still lose much light, in the slit, in the diffraction grating, in the DMD and obviously in the liquid guide. At the end we can say that we have successfully chromatic confocal microscope setup with a working tuneable light source and using an LED and with the unavoidable light losses in the system prevented its use in the chromatic confocal, however the concept was demonstrated suggesting that this would potentially work if the signal-to-noise problem can be solved for example minimising light losses.

5. Conclusion

This study explores the integration of chromatic confocal microscopy and a tuneable light source for advanced 3D surface metrology. The primary objective was to design and test an optical setup capable of performing chromatic depth encoding on a benchtop table, followed by image processing using Python for 3D data reconstruction. The results demonstrated that the chromatic confocal microscope provided precise and accurate measurements, although challenges with light intensity and system alignment were noted.

The tuneable light source experiment demonstrated the capability to create custom spectra using a digital micromirror device (DMD). This innovation allows for the generation of unique spectral patterns that can be used for scanning and precise measurements. However, aligning the system and managing light losses presented significant challenges.

In summary, the study successfully designed and tested a chromatic confocal microscopy setup and a tuneable light source, achieving promising results in 3D surface metrology. Future improvements could include optimizing the light source, minimizing light losses, and refining system alignment to enhance measurement precision and accuracy. Combining the tuneable light source with the chromatic confocal system could offer a robust solution for various metrological applications.

6. Acknowledgments

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7. References

[1] Blateyron F, Artigas R, 2011 Optical Measurement of Surface Tophography Leach R United Kingdom 71-105, 237-258.

[2] Dobson S, Sun P Fainman Y. 1997 Diffractive lenses for chromatic confocal imaging *Rev. Applied Optics*. **36, 20**

[3] Paul C, Sun P, Zhu L and Fainman Y 1998 Single-shot depth-section imaging through chromatic slit-scan confocal microscopy. *Rev. Applied Optics*. **37, 28**

[4] Nikonorov A, Skidanov R, Fursov V, Petrov M, Bibikov S and Yusifovich Y 2015 Fresnel Lens Imaging With Post-Capture Image Processing

[5] Bartczak P, Čerāne D, Fält P, Ylitepsa P, Hietanen E, Penttinen N, Laaksoned N, Lensu L, Hauta-Kasari M, and Uusitalo H 2015 Spectrally tunable light source based on a digital micromirror device for retinal image contrast enhancement. *Rev. Lithuanian Journal of Physiscs*. **55, 3.** 174-181.

[6] Paul C, Pang-Chen S, Lijun Z, and Yeshaiahu F 1998 Singel-shot depth-section imaging through chromatic slit-scan confocal microscopy. *Rev. Applied Optics*. **37, 28**