Investigation of Surface & Sub-surface profile, Techniques of Measurement and Replication of the Chinese Magic Mirror

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ABSTRACT

The Chinese magic mirror is an ancient convex bronze mirror, it reflects parallel light rays to form a unique image within the reflected patch of light by altering the reflected ray paths. Using Phase Measuring Reflectometry (PMR), surface irregularities of a micron range were found to be present on the mirror; these irregularities concentrate and disperse reflected light rays, giving rise to brighter and darker patches on the reflected image, forming a contrast, allowing the unique pattern to be observed. To ascertain location and nature of the surface defects that come in forms of indentations and raised platforms, other measurement techniques were employed. Reverse engineering then facilitated the exploration of reproduction of a very own original Chinese Magic Mirror with the use of optical principles behind the mirror.

Keywords: Magic Mirror, Surface defect, Sub-surface defect, Micrometer defect, Phase Measuring Reflectometry

1. INTRODUCTION

The Chinese magic mirror is an ancient convex mirror made of bronze, first invented during the Chinese Han Dynasty. Just like a normal mirror, this magic mirror reflects an image when parallel light rays are shined on it. The mirror reflects parallel rays to form an image in the reflected patch of light, due to the alteration of reflected path rays due to nano-surface irregularities of the mirror.

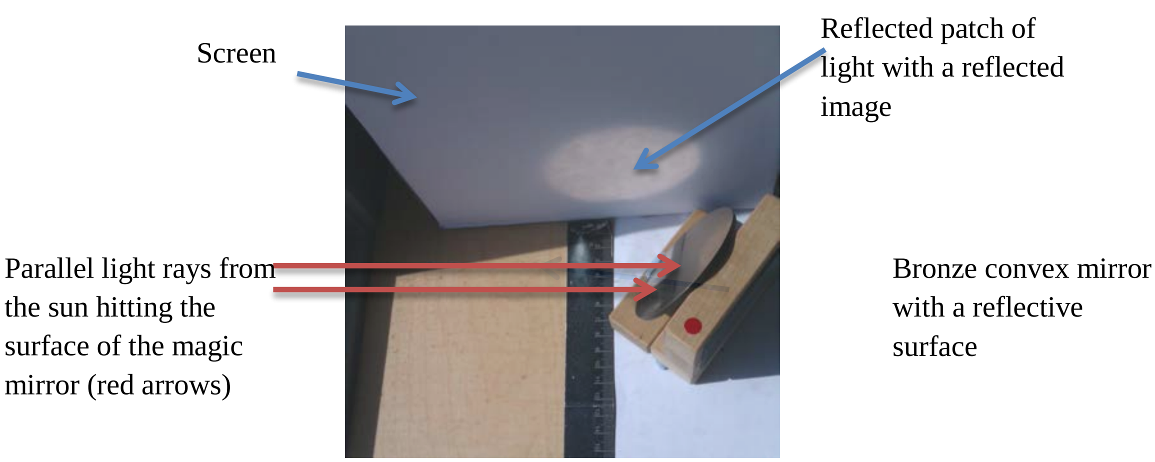

Figure 1: Magic Mirror principle

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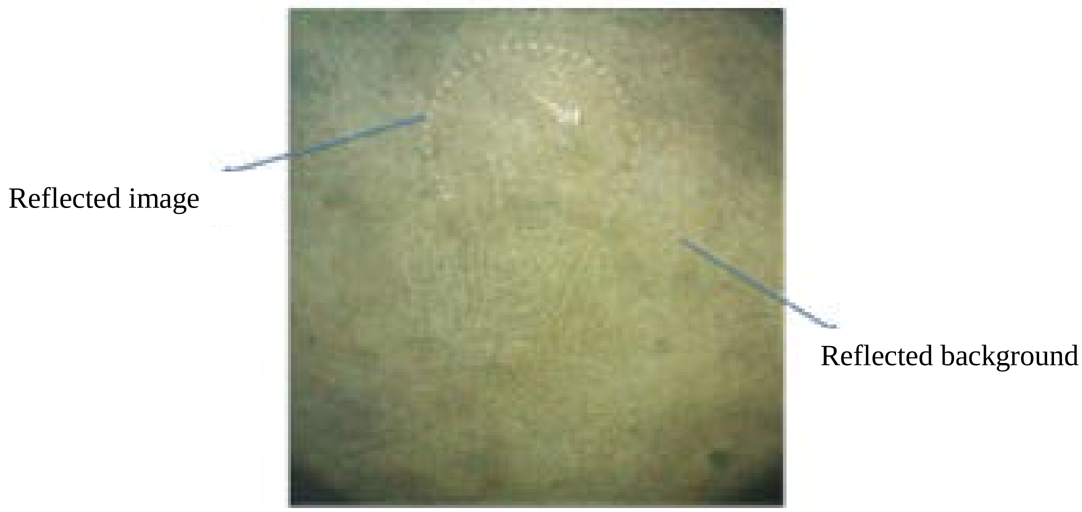


Figure 2: Close up shot of the reflected image. Pattern is seen as a contrast image from the background

There have been many hypotheses to explain how the magic mirror works, but the scientific principles and explanations have not proved their validity with empirical evidence. A theory for the explanation of the magic mirror is that there are slight changes in curvature on the reflecting surface that are dependent on the pattern formed on the back[2][3] during solidification. This process is time consuming. Currently, it is believed that factories have more efficient methods of producing this mirror, but these methods are still unknown.

It has been hypothesized that there are variations of the surface of the magic mirror. Some portions are "depressions", while other parts are slightly "raised upwards". This causes the dispersion and concentration of light spots at different areas, giving rise to patterns[5].

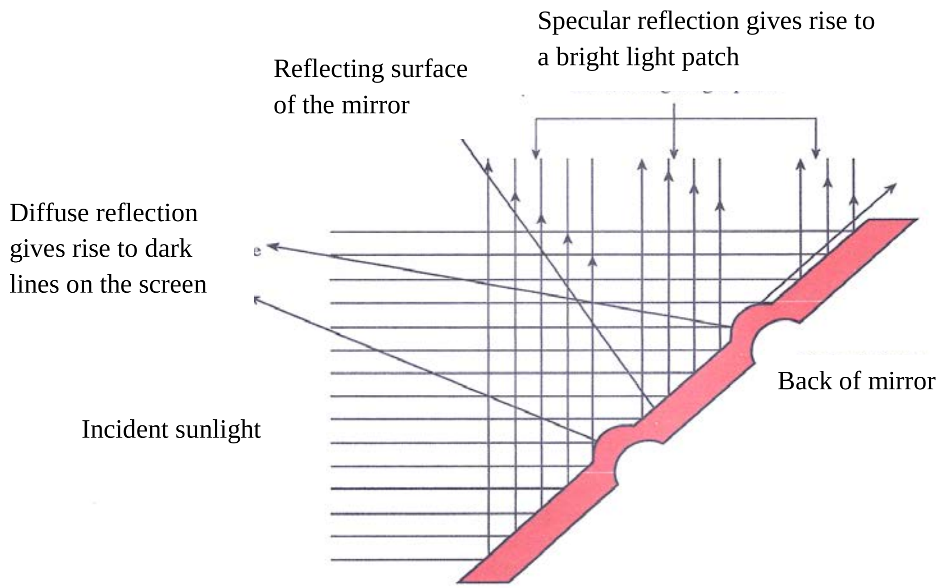


Figure 3: Dents cause reflections to go in different direction from the background.

It is unclear where the indentations are located (on the surface of the mirror, or inside the mirror). There are 2 hypotheses on the structure of the mirror. First, the indentations are on the surface of the mirror (referred to as the “first hypothesis” in this paper). Second, an experiment conducted showed that with no marks or surface irregularities were detected on the surface of any of the magic mirrors under the microscope. A paper suggested that the mirrors had a two layered structure - the reflecting subsurface that gives rise to a projected magic pattern on the screen which is hidden under a polished half-reflecting top layer[1] (referred to as the “second hypothesis” in this paper)

The research is primarily broken down into 3 parts:

I) Examining the structure of the mirror and the nature of the indentations by using various measurement techniques - It would be key to understand overarching concept of the Maric Mirror, so as to better understand the phenomenon of the unique reflected images observed (Section 2).

II) Investigating the accuracy and reliability of measurement techniques - In this process, different measuring techniques were used to measure the unique surfaces of the Chinese Magic Mirror (the sample). The accuracy, reliability and application of the various methods would be discussed in this paper, further exploring the nature of the surface profile of the Magic Mirror in detail (Section 3).

III) Replication and manufacturing of the magic mirror - The conventional process of solidifying a liquid to create the magic mirror is a time-consuming process. We explored new methods of creating the mirror, by taking advantage of modern day technology and machinery. By analyzing the limitations and advantages of the various methods, it would help deepen understanding of this product in the industry when manufacturers look into methods to replicate their own magic mirror (Section 4)

2. EXAMINING THE STRUCTURE OF THE MAGIC MIRROR

2.1 Methodology and Results

4 commercially produced Chinese Magic Mirrors were purchased for the experimentation. The mirrors came in different sizes, 8cm to 12cm in diameter. With slightly convex surfaces, it was noted that all the mirrors had either the same or different image as the casted pattern on the back of the magic mirror as observed depending on the respective mirrors.

In this research, the indentations in the Magic Mirror were to be measured and using a various methods. Prior to the experiments, the surface of the magic mirror was cleaned with propanol, an organic solvent to ensure the surface was clean. An air compressor was used to remove the liquid thereafter. Indentations could be measured without modifying or damaging the original product.

Since it was hypothesized that the indentations are responsible for the production of the reflected image, then the proposed indentations would correspond to the reflected image produced. (For example, the mirror with a reflected pattern of a Buddha should have the indentations arranged in a similar fashion)

Optical Microscope

The surface was observed under the microscope. There were some surface irregularities, but they did not correspond to the reflected image. (The surface irregularities could have been due to the nature of the material used to make the mirror.) If the mirror took on the structure as proposed by the first hypothesis, indentations corresponding to the reflected image should have been observed under the optical microscope. However, since no indentations were observed, the results supports the second hypothesis: The microscope was only able to observe the top layer, the polished surface, which has scratches and dirt. The indentations were underneath the layer, and therefore were not observed.

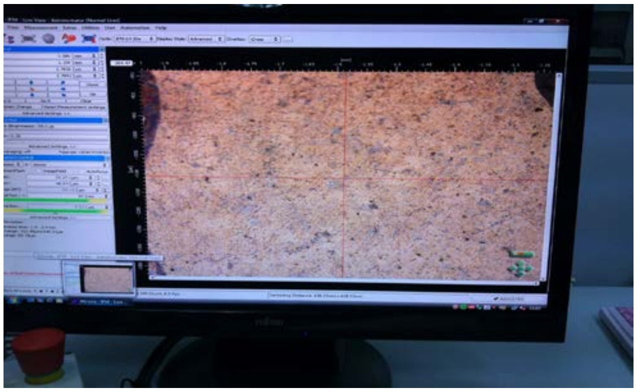


Figure 4: Surface of magic mirror with a surface area of 438.73 nm by 438.73 nm observed under the one optical microscope

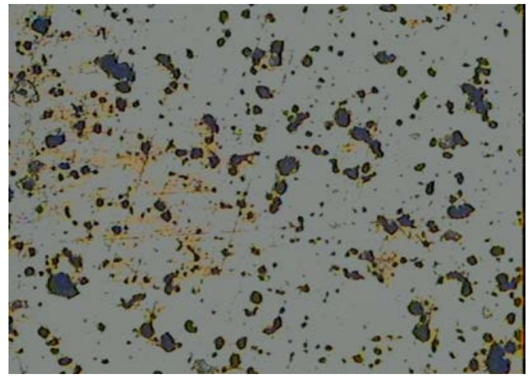


Figure 5: Surface of magic mirror observed with a magnification of (x10 / x15) under another optical microscope

Zygo Interferometer

Fringe patterns were not observed on the Zygo Interferometer. It has been hypothesized that the surface of the magic mirror is convex, which would require a slightly different reference surface plane. The surface of the magic mirror is not entirely reflective due to scratches on the magic mirrors; and the existence of a convex reflective surface also results in the dispersion of light, and not all the light will reflect back to produce fringe patterns.

Laser confocal microscope

The laser confocal scanning microscope can scan a small surface area of a sample size, and has a resolution of 0.2 microns. Under the microscope, there was no significant difference in the surface profiling of the sample. This is because the existence of the subsurface makes the indentations undetectable under the microscope. While some sort of roughness on the surface is required for the imaging of the profile, the smooth surface of the thin layer covering the indentations makes the indentations on the mirror not detected.

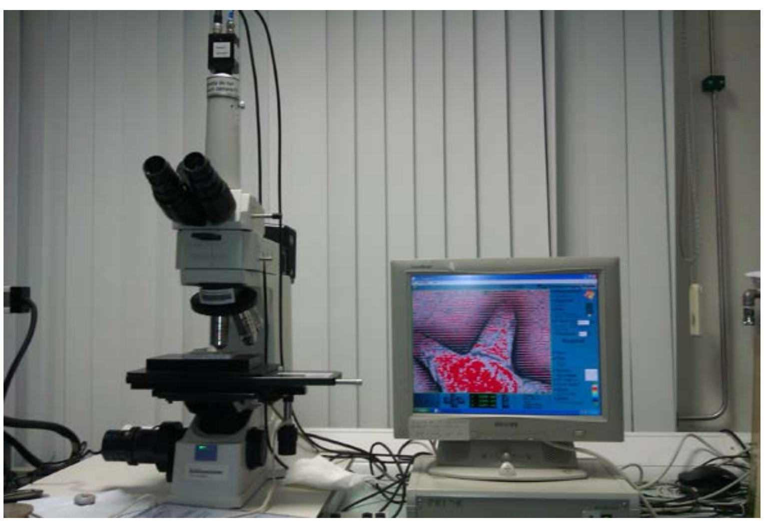


Figure 6: Laser Confocal Microscope

Scanning Electron Microscope (SEM)

2-3 areas of the magic mirror, dimensions 0.5cm x 0.5cm, were marked on 4 mirrors each and observed under the SEM. Some marks could be observed under the microscope, but these marks did not correspond to the reflected image of the mirror. It has been hypothesised that the marks observed were scratch marks on the top most surface of the magic mirror.

Figure 7: Results from the Scanning Electron Microscope

Atomic Force Microscope (AFM)

The AFM measures a small area of the sample, which has to marked out for scanning, prior to the usage of the machine. However, the magic mirror has a polished surface that covers the indentations. Therefore, the scanning probe of the AFM does not detect a difference in the distance between the surface of the magic mirror and the probe, thus not being able to measure the indentations.

Additional Observations

The hypothesized 'indentations' on the mirror are not visible to the naked eye. It was observed that some of the magic mirrors had scratches (due to poor handling of the sample and manufacturing defects). These scratches, however, are visible to the naked eye, hence these scratches are deeper than the proposed indentations itself. If the mirror follows the first hypothesis, then the reflected image will be a pattern of both the indentations and the scratches (since both will affect the reflected image produced.) However, this is not the case. The reflected image is merely an image of a Buddha, with no scratch marks on top of it. Therefore, the second hypothesis would be true to explain the phenomenon observed.

2.2 Conclusions on Structure of the Magic Mirror

Evidence from the above experiments have proven that the magic mirror has a possibility of a two layer structure.

Phase Measuring Reflectometry (PMR)

Sinusoidal fringe patterns were projected onto and reflected off a sample, in this case the magic mirror. Any distortions in the surface of the sample would cause a distortion in the fringe patterns. The 2 cameras captured any distortions in fringe patterns and the processing of distortions captured was then done. PMR makes use of sinusoidal fringe patterns projected onto a reflective surface located remotely from the source to determine the surface profile of the sample. From this, the structure of the magic mirror in the nanometer range observed. The PMR is a well-established method for measuring flat samples. This is the first time whereby PMR was used to measure a sample with a convex surface (the magic mirror. A normal, flat mirror was first placed under the PMR setup to calibrate the machine. Then, the mirrors were tested.

As the PMR was used to measure a convex surface, an integration process involving the subtraction of the global profile completed the conversion of the recorded phase data to height profiles.

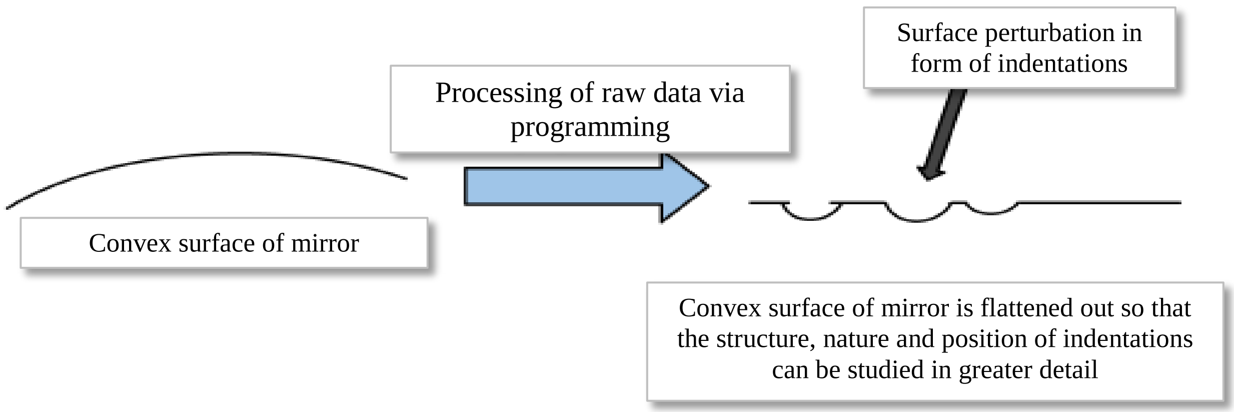


Figure 8: Global profile elimination in PMR

Using the 2-layer structure to explain the results obtained: The mirror has a transparent layer that can allow light to pass through. Gathering fringe patterns that was formed by reflected light was used to collect the data of the indentations. Since the mirror has the transparent layer that allows light to pass through, the light passed through the transparent surface and hit the surface with the indentations, then reflected back

PMR makes use of sinusoidal fringe patterns projected onto a reflective surface located remotely from the source under test to observe the fringe patterns reflected via the surface. Indentations were found on commercially produced magic mirrors, with different depths, ranging from -600 nm to 200 nm: -1000 nm to 1500 nm for the different mirrors respectively.

3. INVESTIGATING THE ACCURACY AND RELIABILITY OF MEASUREMENT TECHNIQUES

3.1 Methodology

Since the Phase Measuring Reflectometry (PMR) has recently been seen as a novel alternative to interferometry as an established method to measure flat surfaces, coupled with the positive results yielded from part (I) of the research, further tests were conducted to confirm its capability and to explore the use of this method for surface and subsurface defect detection, with a Chinese magic mirror is used as sample. It was hypothesised that the PMR's edge in warpage measurement could be translated into measurement of curved surfaces.

A Laser Interferometer, which has a diffraction-limited imaging system and provides an unparalleled accuracy at mid-spatial frequencies, was mounted with a reference plane similar to that of a magic mirror's surface was also used as a control set up. Data from the interferometer was then matched up to that of the PMR, validating sensitivity of the PMR.

As the PMR was used to measure a convex surface, a integration process involving the subtraction of the global profile completed the subtraction of the global profile completed the conversion of the recorded fringe phases data to breath, width and height profiles of the magic mirrors' surfaces.

3.2 Results

The Magic Mirror was identified to carry 3 distinct types of structures, all of which were measurable by Phase Measuring Reflectometry (PMR).

The first structure consists of indentations and/or raised platforms created on the top-most surface of the mirror; these surface defects range from a +600nm to -500nm. The positive sign indicates a raised indentation, while a negative sign denotes a depression in the surface profile. These are translated into darker and lighter observable unique images respectively for positive and negative surface defect profiles.

The second structure consists of general top-most surface perturbation found on the surface of the mirror cause by corresponding indentations found on the underside of the mirror, likely via the manufacturing method. Functioning in a similar fashion to the aforementioned first structure, these ‘ups’ and ‘downs’ of the surface alter the path of reflected light rays with height values of +700nm to -500nm.

Finally, the third structure suggests a vastly different physical makeup of a top reflective transparent layer as well as an underlying layer or “subsurface” on which there are perturbation. When parallel light rays hit the top most surface of the mirror, some incident rays are partially reflected from the smooth top layer while the remaining rays penetrate the top layer only to reflect from the ‘hidden’ layer, commonly referred to as the subsurface of the magic mirror

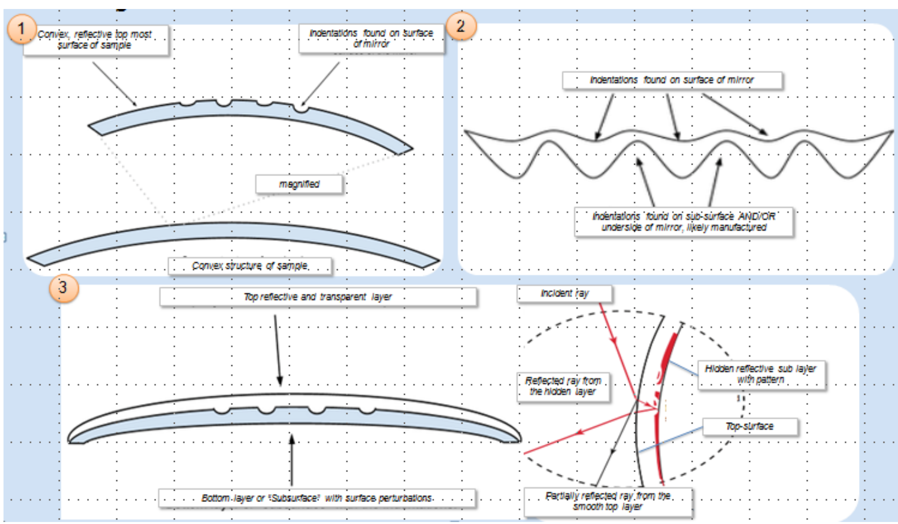


Figure 9: 3 distinct types of structures

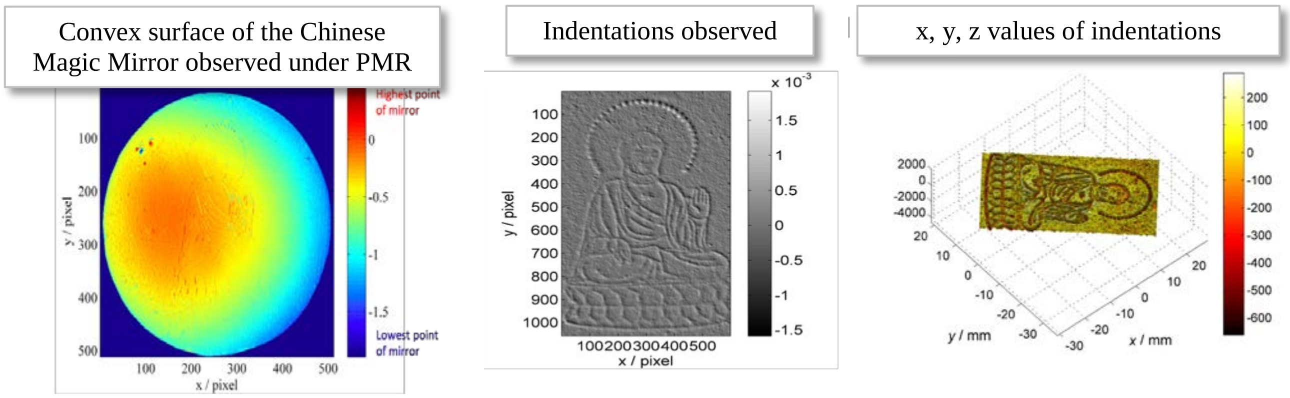


Figure 10: Processed Results from PMR

Dismally, the Laser Interferometer did not yield results as positive. Mirrors and self made samples resembling the mirrors were tested under the interferometer. However the overall distortion of the surface plane resulted in a dis-reference with the interferometer lens, inhibiting accurate measurement; imprecise knowledge of our surface curvature and general surface profile had inhibited the usage of an appropriate interference lens.

3.3 Conclusion of Measurement Techniques

Phase Measuring Reflectometry

The PMR has proved to possess great potential for measurement of large curved surfaces at high resolution without the need of high quality and large reference optics. While is still has areas for improvement in the arena of accurately quantifying profile of object surface via calibration of optical parameters, it is able to serve the purpose of retrieving relative height difference between a large field of view of such a system test surface and a standard reference with a similar profile. Additionally, this has shed light on the PMR's ability to be used to measure warpage and curvature of Siwafers for residual stress and flatness profiling as well as applied dynamically where the surface of liquids could be accurately mapped for distortions caused by external perturbations.

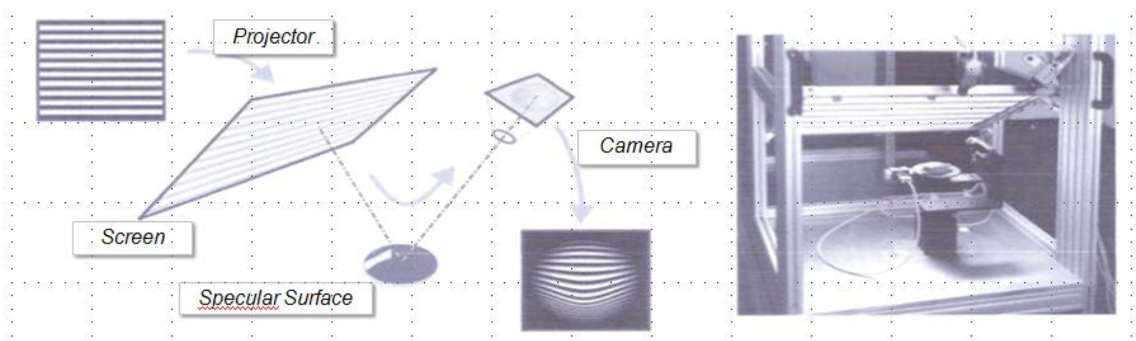


Figure 11: Experimentation set up of PMR

Laser Interferometry

To measure samples with irregularly distorted surfaces, the laser interferometer has proven to be unable to generate a reading accurate or even near-general of the profile of surface a subsurface objects. This has once again highlighted the weakness of traditional measurement techniques when they are procured to deal with samples not manufactured under lab conditions. The laser interferometer would require a reference surface similar to that of the surface profile of the sample in order for the sample to be measured, and to yield accurate results.

4. REPLICATION OF MAGIC MIRROR

4.1 Materials

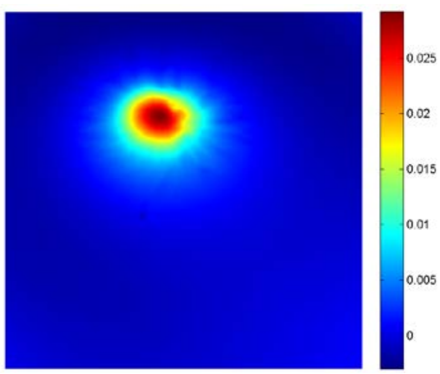
Type of base material

The indentations were created on metal hard discs. These discs had properties similar to the magic mirror. They had diameter of 6-8cm, and shiny reflective surfaces.

4.1 Replication & Results

Creating the indentations by hitting

To recreate the indentations, we used utensils (sharp ends of a spoon, fork) and tools (sharp end of a screw driver). There are two difficulties replicating the mirror with this method. First, it would be difficult to control the force used to hit the disc, hence the depth of the indentations might vary, causing the reflected image to be of different shades of brown. Second, some of the indentations created did not have a diameter that was big enough. If the indentations had too small a diameter, a reflected image would not be produced (as there is not enough light rays to form a reflected image.)



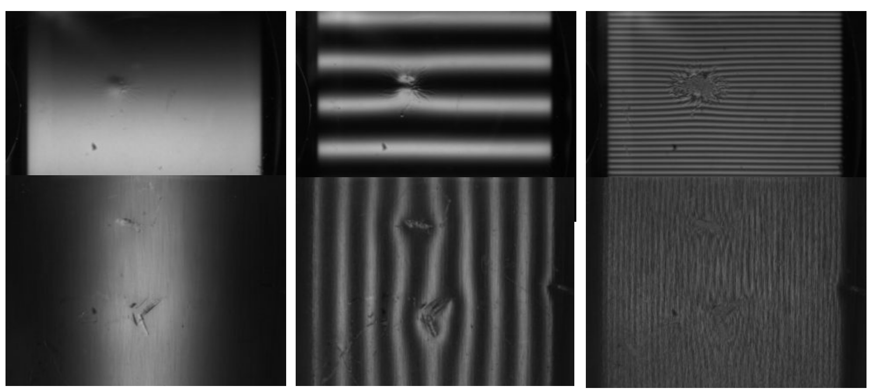


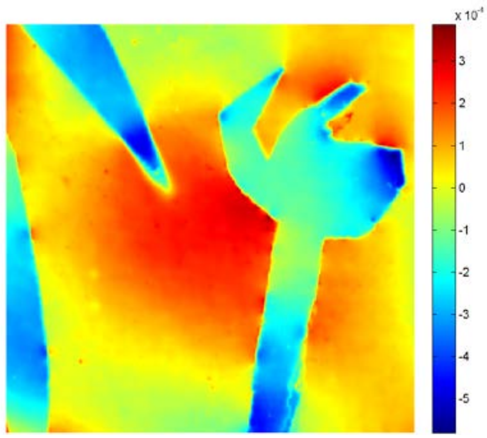
Figure 12: Processed surface defect nature   Figure 13: Succession of raw reflected fringe images captured by PMR

Measurement of samples (created by hitting)

A self-made sample created with the first possible structure of the mirror was tested under the 4D Laser Interferometer. However, since too much force was used to create the indention, the overall surface of the disc was no longer strait. The distortion of the surface plane resulted in a dis-reference with the interferometer lens, inhibiting accurate measurement. Each time the sample was measured, the 4D interferometer yielded different results. Therefore, it can be concluded that the 4D interferometer is not the most reliable method to measure the created samples.

Replication using the Aluminium Splattering Machine

It was decided then that it would be better to use a machine to create the indentations, as we would have complete control over the size, depth and width of the indentation (this ensures uniformity.) The Aluminum splattering machine splatters aluminum at marked out parts of a sample. A layer of aluminum was splattered on marked out parts of the sample. The aluminum coated surface is less reflective as compared to the disc material (that is not covered in aluminum). Therefore, different amount of light rays will reflect off the aluminum and the disc. This produces lighter patches of light (reflected off the disc) and darker patches of light (reflected off from the aluminum), forming a reflected pattern. This method is efficient, and more intricate designs can be created with this technique. Another advantage would be that the splattered aluminum patches resemble a design; hence the sample is more aesthetically appealing (as compared to the indentations created by hitting.)



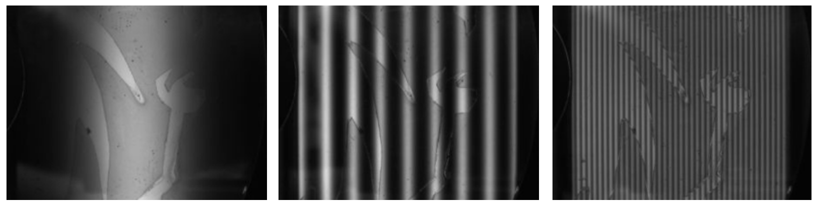


Figure 14: Processed surface defect nature (left); Figure 15: Succession of raw fringe images by PMR (right)

4.2 Conclusion

The methods we have tried were based on the first hypothesis of the structure of the magic mirror. Replication techniques based on the second hypothesis have not been tried out.

5. CONCLUSION

The magic mirror is an ancient artefact that has awed many, professors and students alike. Till today, no one has described the optics behind the magic mirror in detail. Through this research, we have managed to discover the structure of the magic mirror. The magic mirror can be used as an educational tool for the topic of Optics and Light (in Physics, school etc); as well as decorative material due to its aesthetic appeal.

Although the exact magic mirror has not been replicated, we have managed to use an efficient technique to create a sample with high resemblance to the mirror. For real-life application, the mirror can now be easily replicated, customized and can even act as a gift item. If necessary, replication techniques based on the second hypothesis could be explored.

This paper has also discussed the application of the PMR method to measure surfaces and sub-surfaces. More experiments need to be done to prove the validity, reliability and accuracy of the instrument. This can be done by making use of other measuring techniques, such as the 4D interferometer and the white light interferometer.

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