Atomization-based Spray Coating for Improved 3D Scanning

by

Behzad Valinasab
BSc, Islamic Azad University, Central Tehran Branch, Iran, 2003

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Mechanical Engineering

Supervisory Committee

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Abstract

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Obtaining geometrical and physical information of industrially manufactured products or manually created artifacts has increased dramatically in the past few years. These data are usually generated by means of specific devices which are called 3D scanners. 3D scanners generate virtual 3D models of objects which in different fields can be used for various applications such as reverse engineering and quality control in manufacturing industry or data archiving of valuable unique objects of cultural heritage. There are basically two types of 3D scanning depending on whether contact or non-contact techniques are used. Non-contact scanners have been developed to overcome the problems of contacts. Optical methods are the most developed and major category of non-contact scanning techniques. Remarkable progress in computer science has been the key element of optical 3D scanning development. Apart from this improvement, optical scanners are affected by surface characteristics of the target object, such as transparency and reflectivity, since optical scanners work based on reflected light from the object surface. For solving this problem, in most cases the object is sprayed with an aerosol spray to change its characteristics temporarily, e.g. from shiny to dull or transparent to opaque. It is important to apply coating of minimum possible thickness to keep the object geometry unchanged. To study this issue, an atomization-based spray coating system was developed in this thesis research and used in sets of experiments to evaluate the effects of thin layer coating on 3D scanning results. In this thesis, firstly the spray coating system structure and coating specifications will be offered. Then, for appraising the efficiency of atomization-based spray coating in 3D scanning process, some examples are presented. These examples are based on some actual parts from different industries which were used as target objects to be coated and scanned.

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Acknowledgments

I gratefully acknowledge the support from many people during the course of this work at the University of Victoria. Professor Martin B.G. Jun, my supervisor, has provided not only his wealth of knowledge and research experiences in all aspects, but also continuous encouragement and financial support.

I am grateful to everyone in the Laboratory of Advanced Multi-scale Manufacturing (LAMM). The assistance and advice from Reza Bayesteh, Junghyuk Ko, and Salah Elfurjani were invaluable at the initial stage of my work. I am thankful to Max Rukosuyev who has shared with me his knowledge and experience on atomization-based spray coating.

Most of all, I am truly grateful to my parents, Manijeh and Mahmoud, and my brother, Mehrdad, for their love, sincere wishes and support.

Chapter 1 : Introduction

1.1 Background and Motivation

Increasing demand for complex and sophisticated objects has brought up the need for accurate measurement, inspection, and quality control of manufactured parts. Three-dimensional scanning is a process, which meets these requirements by registering the physical and geometrical information of an object. Various methods of 3D scanning have been developed so far. Optical 3D scanning is one of the fast and easy techniques for capturing surface information of manufactured parts. Because the optical scanning method works based on reflected lights from the object surface, surface characteristics of the object play an important role in the accuracy of the measured dimensions. Scanning becomes difficult for black, shiny, or transparent surfaces because too little or too much light is reflected from the surface. For these surfaces, coating is typically applied to change the surface characteristics, using a spray can. However, coating adds thickness of around 10 – 50 µm to the surface, causing changes in the measured dimensions. Also, uniform coating over complex surfaces and features such as corners, pockets, and holes is difficult with conventional spray cans. Therefore, it is important to consider an alternative device to apply coating for objects with difficult-to-scan surfaces.

3D scanning is defined as the generation of a 3D virtual computer model of a target object with the help of acquired data from the object surfaces. The 3D model is usually generated by converting a measured point cloud into a network of triangles. 3D scanning is widely in use in different fields and is required for various applications. In the manufacturing industry, 3D scanning and modelling is one of the main tools for reverse engineering. It is also utilized for inspection and quality control by comparing the original part model with the manufactured part's 3D model. In the cultural heritage field, 3D scanning is used for archiving valuable artifacts; motivations include virtual museums creation, educational resources, and documentation in case of loss or damage. Also in medical sciences, 3D scanning is used for producing different prostheses [1].

3D scanners can be classified as contact or non-contact devices [1]. In contact techniques, the object is scanned by physical touch of a probe. The scanner probes an object which is fixed on a precision flat surface plate and then generates a cloud of measured points. The coordinate measuring machine (CMM) is the best example of contact scanners. However, in this method, the scanning is carried out by making physical contacts with objects, and thus, the scanning process of a complicated object can be time consuming. In addition, because the probe moves around to measure various spots, it may have some limitations to probe complex surfaces with many features.

To overcome the problems of contact scanners, non-contact techniques have been developed and utilized for years. These techniques have experienced significant growth during past years. Remarkable progress in computer science has been the key element of non-contact 3D scanning development. Mostly in non-contact scanning, surface information of an object can be registered with the help of radiations reflected from the target object (reflective technique). In some other non-contact techniques, modelling is done by passing radiations through the object (transmissive technique).

Based on the radiation type, reflective methods are divided into optical and non-optical methods [2]. SONAR (sound navigation and ranging) is the best example of non-optical scanning devices and is usually used to map the sea floor by using acoustic signals. On the other hand, optical scanning techniques use light reflection to model an object. Some optical scanners work based on the speed of light (time of flight scanners) and scan objects with the help of round trip time of a laser or other light source between the scanner as the emitter and the object as the reflector. Other optical scanners work based on triangulation. In triangulation, a spot or a pattern of light – produced by a laser or a projector - is projected on a surface. A detector (usually a CCD camera) senses the reflected light from the object. Based on the positions of the projector, detector, and the object - which determine a triangle - and the distances between them, the software can compute the depth of each point on the surface with reference to a specified scanner coordinate system and then convert it to a 3D point [3].

The quality of reflected light is influenced by the reflective ability of a surface which is called albedo. Albedo can be defined as the proportion of the incident light or radiation that is reflected by a surface. Based on that, optical methods are affected by those surface characteristics of an object that can affect the light reflection, such as transparency, glossiness, and color. That is why an object with a white surface compared to a black one, is an easier target for 3D scanning as it has better reflective properties [4].

In case of a rough surface, light can be reflected in a diffuse way and bounces back in all directions from the surface. However, when light strikes a shiny surface, the reflection occurs in a specular way and light bounces back in a unique direction. In case of a translucent object light penetrates more into the object and reflects back from inner parts but not from the surface. Shiny and translucent surfaces cause noisy data in scanning results. Various methods have been developed to filter the noisy and unwanted reflection from the ideal ones. E. Trucco et al. used more than one camera for one laser source at the left and right side of the object to eliminate the noisy data. After adjusting cameras to have the same origins, two cameras can generate two identical range images. For a specific light pattern over the surface, if more than one point is captured, all points can be deleted to filter the noisy data [5]. Chen, Tongbo, et al. presented a method for scanning translucent objects by separating the direct reflection component from any global illumination effect by combining phase shifting with polarization filtering [6].

While various scanning techniques have been developed in computer graphics to solve the issue of shiny and transparent objects, the problem still exists with most optical scanners, especially with formerly developed ones. The main purpose of all newly-developed techniques is to make various objects scanable regardless of surface properties. Based on this idea, coating the surface of an object has proved a suitable approach for scanning objects with difficult surfaces. The goal of this approach is to change the surface characteristics temporarily by covering the object with layers of appropriate pigments to ease the scanning process. In most cases target objects can be sprayed with specific aerosol sprays quite fast but usually an aerosol spray applies layers of coating with thickness of more than 10 micron which is not ideally flat and uniform. This may increase and modify the dimensions of the object to the extent that undesirable changes in its geometry occur. Apart from adequate thickness, the applied coating should have suitable optical properties and should scatter light from the surface completely. Titanium dioxide is the most important white pigment which has very high refractive index. This helps the pigment to increase the “Hiding Power” with minimum thickness. Hiding Power is an optical property which is used to describe the light-scattering efficiency of a pigment. Pigments with high refractive index increase the hiding power with a very thin layer. Based on the mentioned criteria, a newly designed atomization-based spray system was developed and tested in sets of experiments to study the outcome of thin layer coating on scanning results while objects with difficult surfaces are in use. Titanium dioxide white pigments were used as the coating material. The coatings were done on glass slides and mirror-polished gauge blocks which were not scan-able due to their transparency and reflectivity, respectively. The scanning process was done by means of a structured-light 3D scanner and a laser scanner in order to compare the scanning results for at least two different techniques.

In this thesis, at first a short description of three-dimensional scanning and measurement and its applications is presented and then various major 3D scanning techniques and their subcategories are presented. Furthermore, atomization of particles and some atomizing techniques such as pressure jet and ultrasonic atomization are discussed briefly. Then in the next part a brief description of hand held nuzzle manufacturing is given. The experiment section describes how various microscope glass slides and gauge blocks were used as basic samples of transparent and reflective objects. They were coated with the help of an atomization-based spray coating system with various thicknesses and then they were scanned to study the results. Finally in last part the efficiency of an atomization-based spray coating system on the 3D scanning process was studied by using some actual parts from different industries.

1.2 Research Objectives and Scopes

In general, three main objectives are considered in this thesis:

- Development of an ergonomic nozzle that can be integrated with an atomizer to form a spray coating system;

- Modify the atomization-based spray coating system that is capable of applying thin layer coating with less than one micron thickness on various objects that can be removed easily from the surface; and
- Evaluating the 3D scanning results of difficult surfaces after applying atomization-based thin layer coating.

1.3 Thesis Outline

The aim of this thesis is to provide and evaluate a new spray coating system to improve 3D scanning quality. Chapter 2 offers an introduction to 3D scanning and various scanning techniques and after that presents the notion of atomization of particles and some atomizing techniques such as pressure jet and ultrasonic techniques.

In Chapter 3, the development of a spray coating system and its new integrated nozzle is offered.

In Chapter 4, the efficiency of the thin layer coating system's on 3D scanning is evaluated and the coating properties are studied by means of a surface profilometer.

In Chapter 5, the spray coating system is evaluated with the help of some actual parts with difficult surfaces from various industries.

Finally, Chapter 6 summarizes the research work and outlines future work.

Chapter 2 : Literature Review

2.1 Non-Contact 3D Modelling and Measurement Techniques: A Review

2.1.1 Introduction

Development of manufacturing industry and production of complex and sophisticated objects have brought up the necessity of accurate measurement, inspection, and quality control of manufactured parts. Besides, the demand for obtaining physical specifications and recording the information of formerly manufactured and created objects has been increased dramatically in past years. The obtained data help to reproduce a specific object by means of reverse engineering. As the other fundamental application, acquired information can be used in data archiving, e.g. in cultural heritage, for documentation in case of loss or damage or for creating virtual museums [7]. Many methods have been developed to obtain physical information of objects as precise as possible. These methods outcome is usually a 3D model which later can be used for object measurement and inspection.

Despite significant development, 3D modelling still encounters multiple limitations. From accurate contact methods to rapid optical techniques, they all face barriers regarding their methods of working. This shows that in complicated projects, as a solution, a combination of different 3D measurement and modelling techniques can cope with all obstacles. Development in computer science assists 3D metrology for further advancements especially in non-contacts techniques. These progresses expand 3D modelling and measurement applications from manufacturing industry to animation, medical science, cultural heritage, and more. 3D measurement and modelling techniques can be divided into contact and non-contact methods. This review defines 3D scanning and introduces its various techniques and their applications.

2.1.2 3D Modelling, 3D Scanning

Three-dimensional modelling is generation of 3D virtual model in computer with the help of acquired data, usually from an object surface. 3D model is mostly generated by converting a measured point cloud in to a network of triangles. 3D modelling is done with the help of advanced devices called scanners. 3D scanner is a device which gathers the outer information of an object. Scanning process results in a large quantity of points in an organized pattern which is called point cloud. Then, with the help of the linked software, the scanner creates 3D digital model of the object [1].

2.1.3 3D Modelling Applications

Three-dimensional modelling is required in various applications. It is utilized in manufacturing industry for inspection and quality control of generated parts. With the help of modelling software, it is the new tool of animation and film industry. With new improvements in modelling techniques, it is widely utilized in archiving cultural heritage with different motivations; for creating virtual museums, as educational resources, and for documentation in case of loss or damage [8-10]. Furthermore, 3D modelling is applied for medical purposes in producing different prosthesis. It is also one of the main tools of reverse engineering process in obtaining physical specifications of an object [11].

2.1.4 3D Modelling and Measurement Techniques

3D modelling and measurement techniques can be divided in to two main categories. Based on 3D scanners technical way of operations they can be contact or non-contact. In contact techniques the object is scanned by physical touch of a probe while in non-contact methods, no contact happens between the scanner and the object, and in most cases the scanner can probe the object with the help of emitted radiation from the object surface. Each one of scanning methods has advantageous and disadvantageous and according to requirements and demands, the appropriate one can be selected. In most of complicated projects, e.g. modelling cultural heritage, a combination of multiple scanners is the solution to achieve the best result [12]. Therefore recognizing each method and its specifications, as well as being aware of project requirements and considerations, result in selection of the best scanning techniques and devices [1, 13]. In the next part some criteria of selecting the appropriate scanner are described.

2.1.5 Considerations of Selecting a Proper Scanner

Different criteria can be taken in to consideration for choosing a proper 3D scanner for a specific application. Although in some projects a combination of various scanners is in need to finalize the task.

Accuracy is the most important criterion for choosing an appropriate scanner. In most cases the precision of captured images and final data are the crucial part of the project. Although in some projects and depending on different demands and limitations, other considerations can push accuracy a side.

Scanning can be a time-consuming process when high point densities are needed for high resolution. Scanning 1000 points per second finishes the project 10 times faster than scanning with rate of 100 points per second. This can be important in some projects which limited time is considered for finishing the task. Therefore the scanning **speed** can be an important issue in a project and long process of scanning (from initial image capturing to final data processing and modelling) can be a barrier for achieving the desired goals in specified period.

Resolution can be define as the ability of imaging the details of an object. In many cases scanning with high resolution is needed and can be one of the major demands of a project.

Scanners with mobile and adjustable cameras are able to cover larger **field of view** compared to fixed scanners. Having Cameras with flexible mounting situations can help the scanner to have variable field of view to probe large and small objects in far and close distances.

In many projects, a **light** and small scanner is in demand. In this case, the scanner can be easily carried from one side to the other side. Different companies produce hand-held scanners to solve this issue for their customers.

Beside hardware, the **scanning software** plays a critical role in 3D scanning and modeling. It can speed up the process of scanning. Simple and user-friendly software helps customers to work easily with the equipment.

3D scanners mainly use for precise measurement and modelling of objects, but in some cases, users like to have high quality images with complete texture information (e.g. surface color). Different types of **camera** for a scanner can solve this issue. In this case an adaptor can be considered for the scanner for making it flexible for mounting different cameras [14].

2.1.6 Primary Classification; Contact and Non-Contact Methods:

2.1.6.1 Contact Method

In contact techniques the object is scanned by physical touch of a probe. The scanner probes the object which is rested on a precision flat surface plate and then generates a precise 3D model of it. Coordinate measuring machine (CMM) is the best example of contact scanners (Figure 2-1). Contact scanners generate highly accurate model of objects but as it is evident from their name, it happens by making contacts with objects, which according to the project type can be a major disadvantage for this method. Therefore contact methods can be effective for industrial purposes, while for scanning valuable object, e.g. in cultural heritage, this method would be rejected due to the mentioned point. In addition, contact methods are quite slow as the mobile arm of the system should move around for scanning various spots and by each contact the information of only one spot can be obtained. Then the whole process of scanning would be quite long. In some cases, for solving this problem, a non-contact scanning sensor would be mounted on the system at the end of probing arm and the scanner probe the object with higher speed. Also some experiments have been conducted on building a CMM with a multi probe measuring system consists of a structured light sensor and a trigger probe [15].

One of the other disadvantages of the contact scanners is that they are large and fixed and there is a maximum size limit for objects to be scanned. Also for the scanning process the object must be transported to the scanner rather than vice versa. The largest CMMs can measure objects up to a few metres in size with an accuracy of tens of micrometres, but such systems are prohibitive in most projects.

Figure 2-1: Coordinate measuring machine

2.1.6.2 Non-Contact Method

Non-contact methods are classified in to reflective and transmissive techniques. Generally, in reflective techniques, depends on the scanner method of operation, dimensions of an object can be measured with the help of radiations reflected from the target object. Radiations can be light, sound, and etc. But in transmissive techniques no reflection happens and radiations pass through the object for modelling purpose.

Based on the radiation type, the reflective techniques divided in to optical and non-optical. Optical method is the basis of the most of newly developed and efficient scanners. Based on adoption of the optical technology, optical method is categorised in to active and passive approaches [16].

Active optical scanners are based on a source of light, like a projector, which emits light on the target object, and a receiver which is typically a CCD (charged-coupled device) sensor and acquires the surface data through capturing multiple images of the object. In active methods the 3D coordinates of surface spots are obtained and would be used for 3D mesh generation of the model. In passive methods, scanners do not emit any kind of radiation themselves, but instead rely on detecting reflected ambient radiation. Passive scanners provide models that need further processing. Most scanners of this type detect visible light because it is a readily available ambient radiation. Passive methods can be very cheap, because in most cases they do not need particular hardware but simple digital cameras [2, 17]. Figure 2-2 shows a basic taxonomy for non-contact scanning technique.

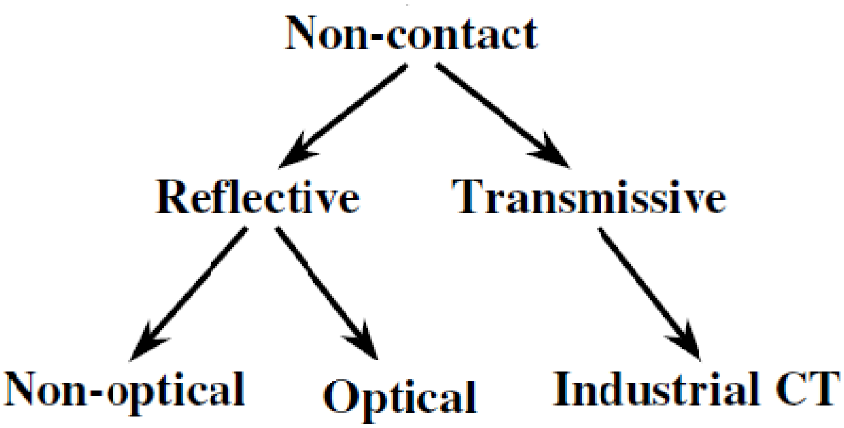

Figure 2-2: Non-contact basic taxonomy [2]

2.1.7 Active Methods

Optical range sensors like time-of-flight, phase-shift, and triangulation-based instruments directly record the 3D geometry of surfaces by producing quantitative 3D digital representations (point clouds or range maps) in a given field of view. Range sensors are getting quite common in the mapping community and heritage field, despite their high costs, weight and the usual lack of good texture.

2.1.7.1 Time of Flight

Time-of-flight 3D scanner is an active scanner which collects 3D coordinates of a given region of an object surface with the help of round trip time of a laser or other light source between scanner as the emitter and the object as the reflector. During measurement, a laser pulse is reflected back to its emitter from an object and is received by a sensor. With knowing the round-trip time of the laser between emitter and the object (t) and speed of light (c), the distance (d) in between can be calculated through (2.1):

$$d = c.t/2 \tag{2.1}$$

The time-of-flight laser scanners are suitable for probing large and distant objects [2]. Like most optical methods, this method has problem with scanning reflective surfaces and the quality of the results depends on the surface characteristics of the scanned object.

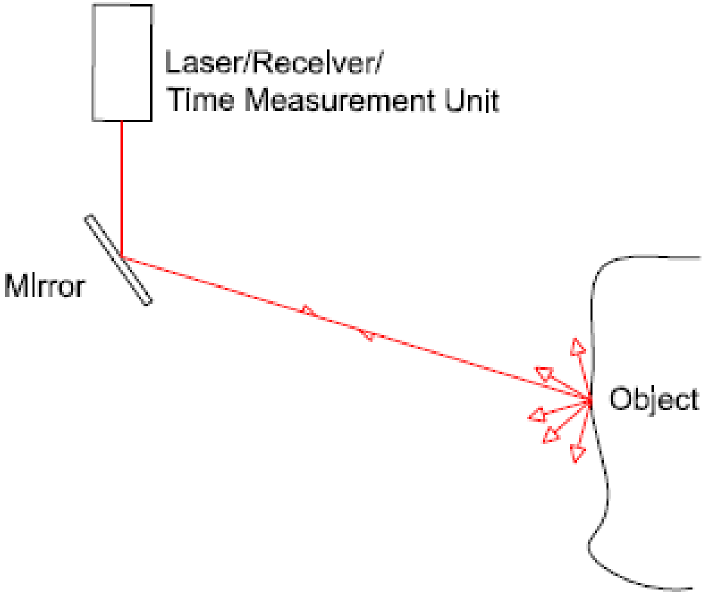

Figure 2-3: Time of flight principle [14]

2.1.7.2 Triangulation

Most of newly designed 3D scanners work based on triangulation. In triangulation, a spot or a pattern of light – produced by a laser - is projected on an object. A CCD (chargecoupled device) camera or a position sensitive detector (PSD) senses the reflected light from the object. Based on the position of the projector, camera or detector, and the abject - which shape a triangle - and the distances between them, the software can compute the depth of each point on the object with reference to specified scanner coordinate system and then convert it to a 3D point [3].

Triangulation is a fast method of 3D scanning and data acquisition. Despite time-of-flight laser scanners, triangulation is a highly accurate method but with limited range to some meters. Similar to other optical techniques, this method has limitation in scanning of reflective and transparent objects.

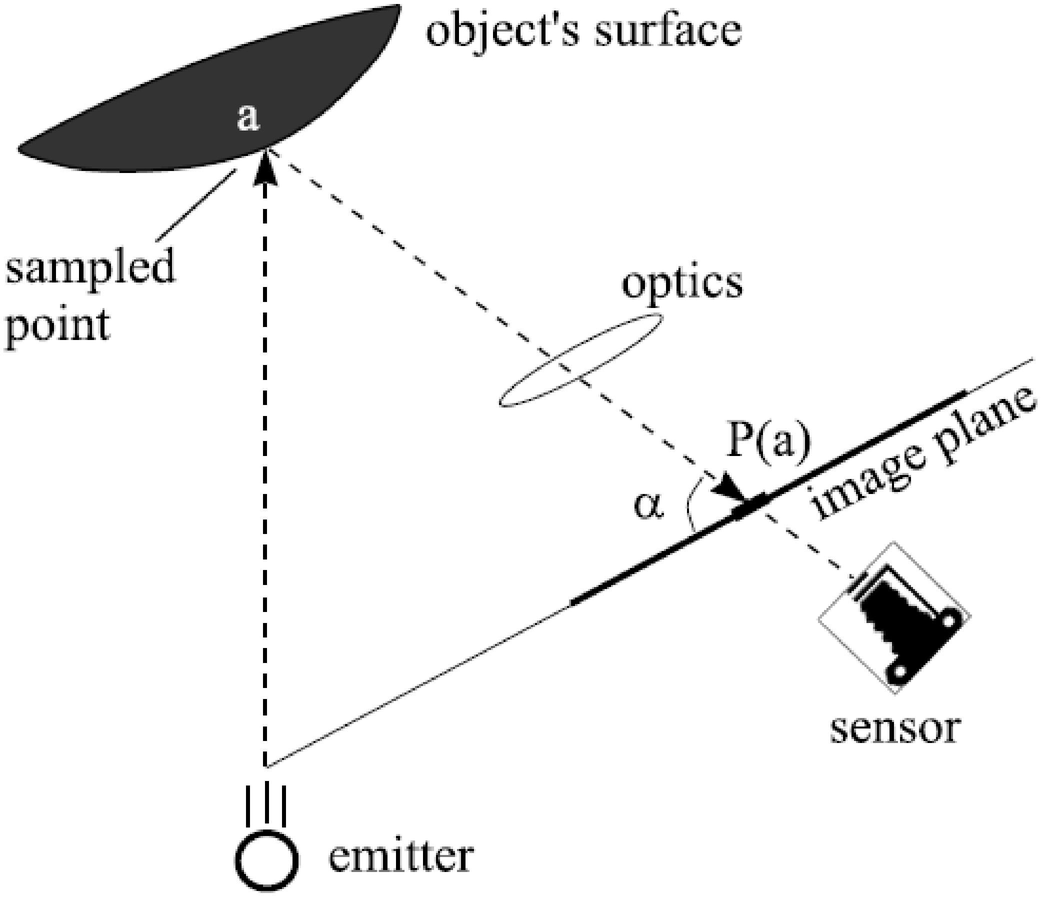

Figure 2-4: A typical optical scanner based on triangulation [17]

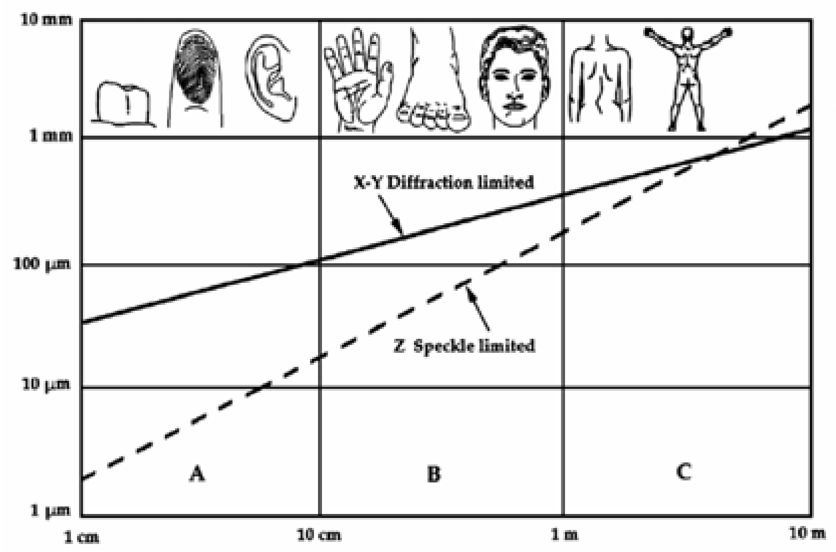

Figure 2-5: Physical limits of 3D optical measurements based on laser projection and triangulation [18]

Single Camera. This type of scanner consists of an emitter device at one corner and a sensor (mainly a camera) at the other corner which senses the laser spot on the object. The spatial position of the spot can be calculated from the subsequent triangle. This is one of the most precise techniques for measurement of small objects in close distance where it is more accurate than ranging scanners like time-of-flight [14].

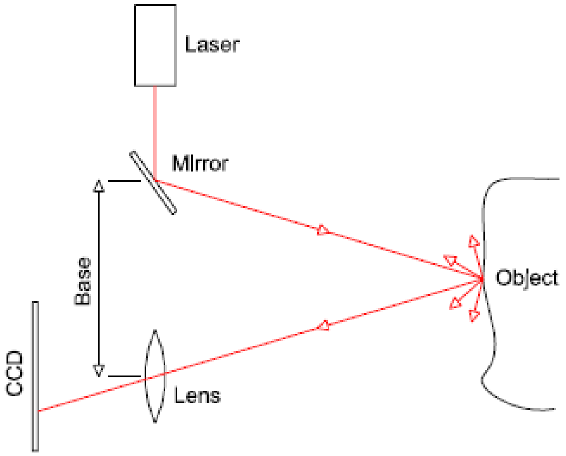

Figure 2-6: Triangulation principle: single camera solution [14]

Double Camera. A different method of using triangulation is to utilize two sensors (mainly camera). Each sensor is located at one end of the base line (a line between sensors) and the projector is located in between. The principle is like single sensor system and the system utilize the triangles relations to calculate spots distances [14].

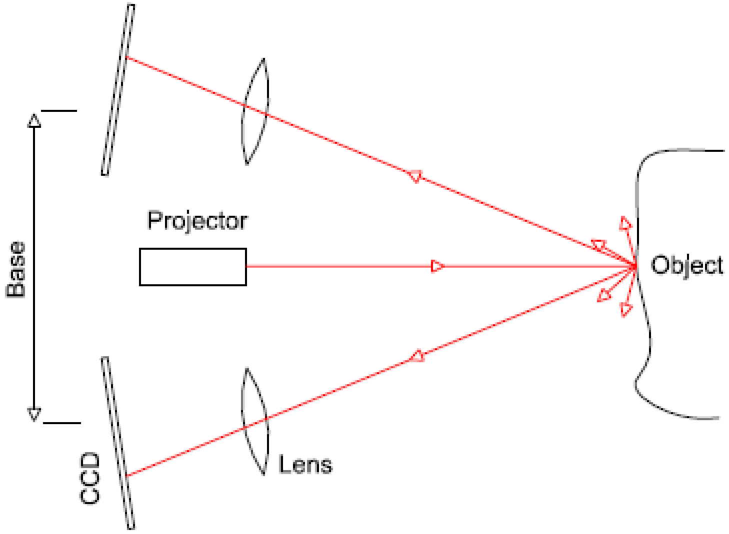

Figure 2-7: Triangulation principle: double camera solution [14]

2.1.7.3 Structured Light

This active optical method of 3D scanning can provide accurate information of the scanned object with the help of projecting structured or coded light on the surface. The system is consists of a projector and a digital camera (or two). Structured-light scanners use triangulation principle to calculate the depth of points on an object surface.

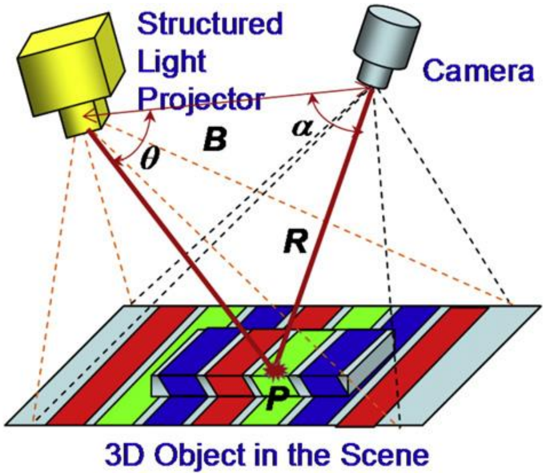

Figure 2-8: Illustration of structured light [19]

As it can be seen in Figure 2-8, the projector, the imaging sensor, and the object make a triangle and the distance between a point on the surface to the sensor can be expressed as (2.2) [19].

$$R = B\frac{\sin(\theta)}{\sin(\alpha+\theta)} \qquad (2.2)$$

The camera(s) is used to capture images of the object under projected structured light. In some scanner a video projector is utilized as it has the advantage of producing different patterns. Both devices are controlled by a software tool. The sensor can detect and calculate the depth of different surface points by considering deviations and deflections of the projected pattern on the surface. Over many years this method has been used for the measurement of the object and during this period there have been many developments on it which has made it a common tool for experts in scientific communities and also for non-experts in fields such as cultural heritage studies. In most cases and due to the object size and geometrical features of the object, multiple scanning must be performed from various angles and directions to cover the whole area and surface of the object. Next, various scans must be integrated and registered together to complete the modelling procedure. Registration defines as combining and transforming of various scans to a common coordinate system. Finally, the outcome of the scanning process must be filtered. This method is affected by the reflectiveness of the object surface. Structured light scanners can provide an accurate model of small and medium size objects up to the size of human or a statue [3, 20-22].

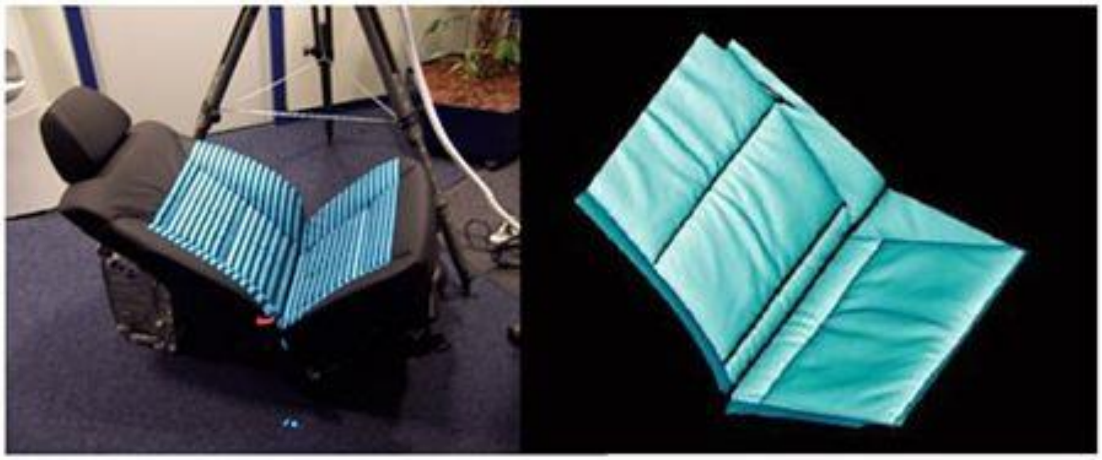

Figure 2-9: 3D survey of a car seat

2.1.7.4 Moiré Technique

A moiré pattern is an interfering pattern created when two gratings are overlaid at an angle. This phenomenon has been conducted for 3D depth measurement of objects in moiré technique. The moiré method can be divided in to **shadow** and **projection** moiré.

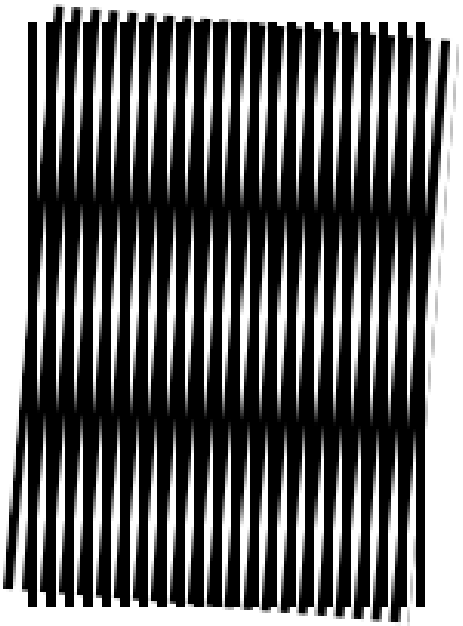

Figure 2-10: A moiré pattern

Figure 2-11 shows a pattern for shadow moiré. In shadow moiré technique, a grating, g, with equal spaced openings, d, is located in front of an object and a light source spreads the grating shadow on the object surface. Light lines, m, passing through the openings generate some illuminated points, p, on the object surface. From another point of view, the grating filters its shadow and the illuminated points can be seen from the adjacent openings (1d distance) through the lines n. A pattern would be generated from the intersections of m and n lines on the object surface from the adjacent pairs of openings. Other patterns are generated from the intersections of m and n lines considering openings with the distances of 2d, 3d, etc. These patterns would be analysed then for computing the surface reliefs.

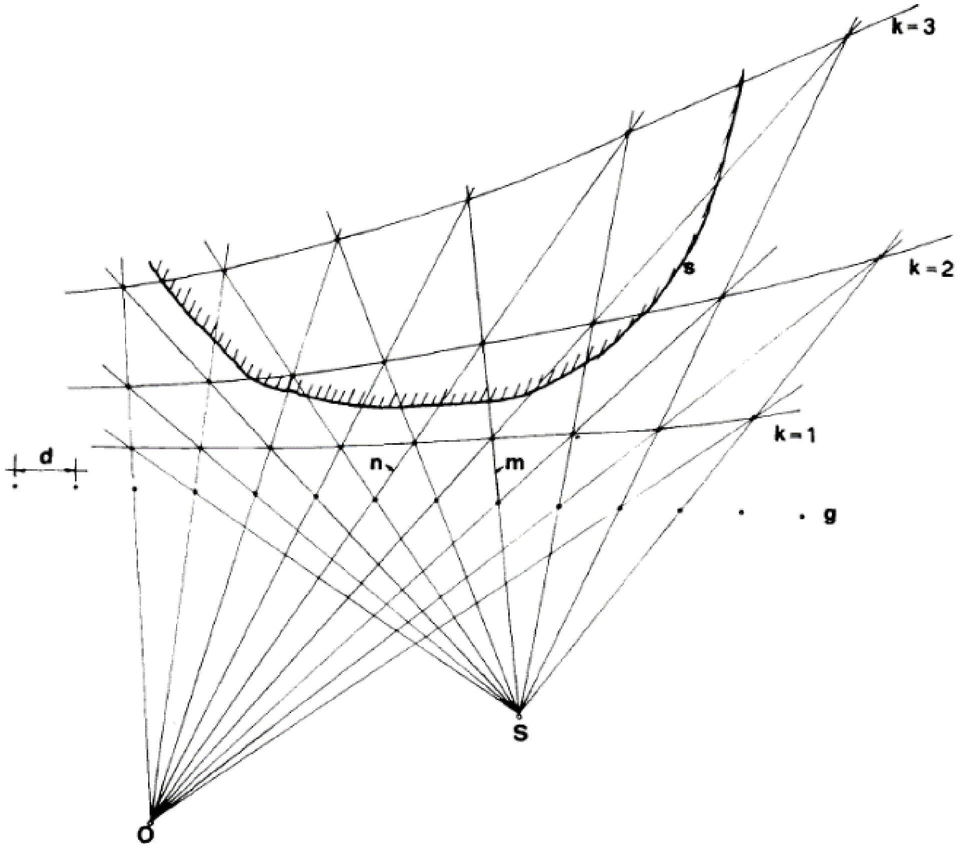

Figure 2-11: Shadow moiré [23]

In projection moire a pair of line gratings of identical pitch is used; one is called the projection grating and the other the viewing or reference grating. Interfering between these two gratings causes a number of moiré fringes to appear superimposed upon the surface of the object which can be observed by a CCD camera. The sensitivity of the moiré method depends on the pitch of the gratings used [23].

One of the major application of the moire technique is in dimensional metrology. It allows on-line inspection of mechanical parts that can be instantly compared to a master part by difference contouring [24, 25].

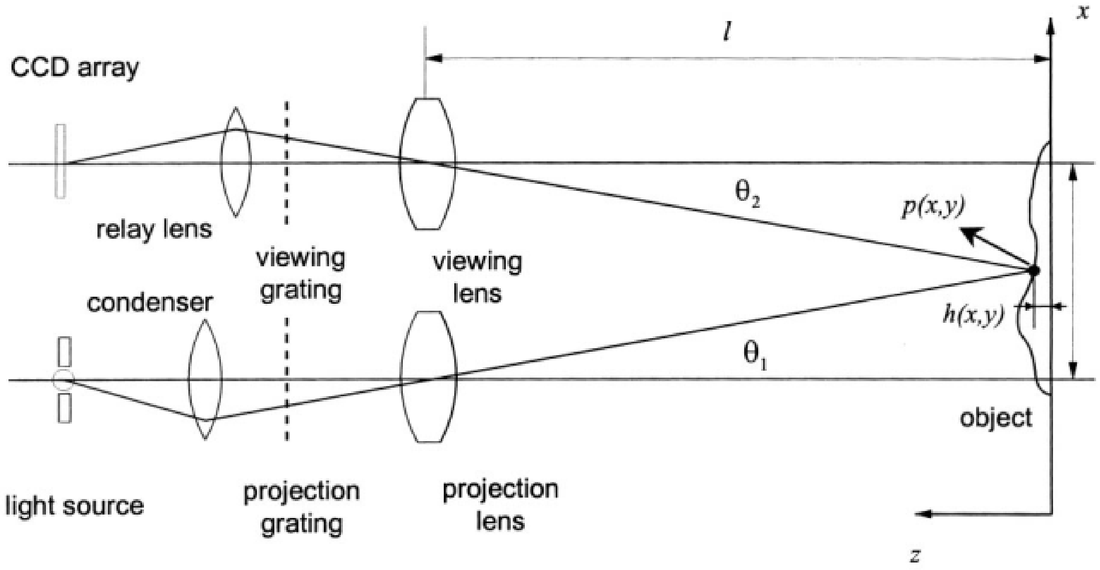

Figure 2-12: Projection moiré [26]

2.1.7.5 Computed Tomography

Computed tomography (CT) scanning is a well-established method in medical diagnostics. It has been in used for many years in medical imaging. Nowadays CT scanning is utilising in other industries for further applications. Beside medical imaging, CT has been employed for material analysis and testing, e.g. for observing the inner structure of material for defect [27]. Recently, CT has been utilized in manufacturing technology for 3D measurement applications [28].

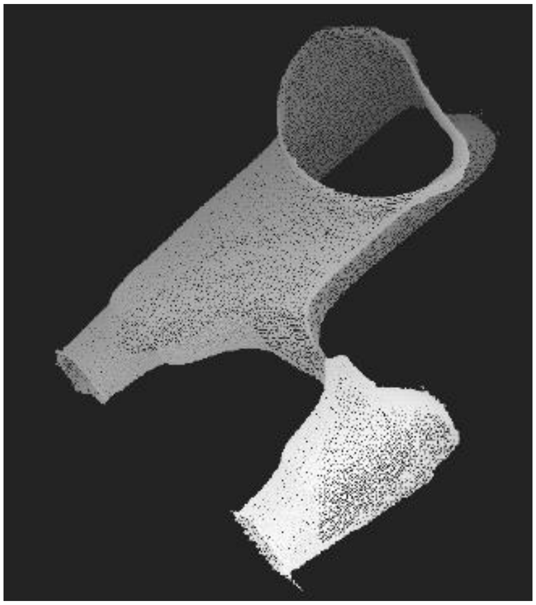

Figure 2-13: Point cloud generation by CT [29]

There are several operational differences in various applications of CT scanning. In general, CT systems consist of four main parts; x-ray source, x-ray detector, kinematic system, and data processing software. In medical CT scanning, the object (patient) is immobile and the x-ray tube and the detector rotate around the object, while in metrological CT scanning, the object rotates in the space between the x-ray source and x-ray detector. Also, in medical applications, limited amount of radiation and power would be used to protect the patient, whereas for industrial applications higher radiation and power would be used for more penetration to achieve measurement and quality control demands.

Because of unique features of CT scanning, it is the only measurement technique which is able to measure both the outer and the inner geometry of a component without cutting or destroying it. In addition, CT can test and control the internal quality of work piece without having access to inner layers. In other words, CT technology can perform dimensional quality control and material quality control simultaneously which can be a major advantage of this method compare to other non-contact techniques of 3D measurement and modelling.

Due to this exclusive property of CT scanning, this method may be sit instead of most measurement techniques (e.g. optical systems) in future [29].

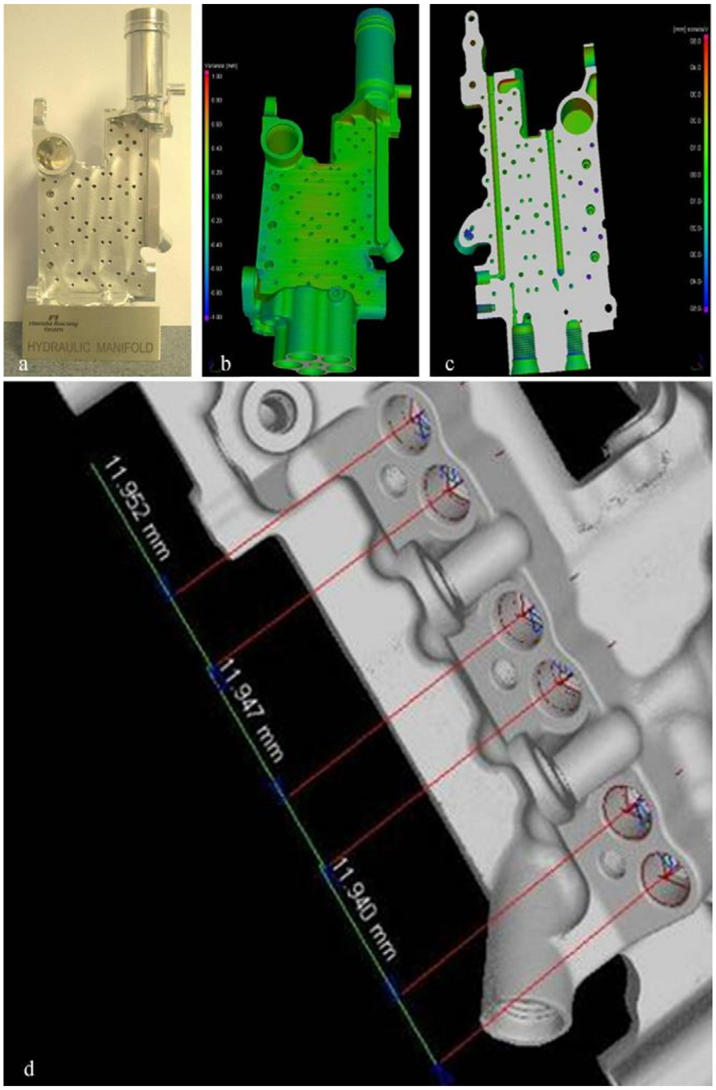

Figure 2-14: CT control of individual dimensions (bottom) and comparison of outer and inner geometry with CAD model (top) [30]

2.1.7.6 Sonar System

Knowing the underwater world of oceans and seas has been in great demand of geologists and biologists. They have been interested to map the sea floor for better understanding of geological process that forms the earth. Cameras have been in use for acquiring various data such as physical properties of the seafloor but inappropriate conditions of the underwater make the acoustic sensor more reliable than imaging device. Currently, SONAR (sound navigation and ranging) is the most widely used system for under water imaging. The fundamental of sonar system is similar to time-of-flight method. An acoustic signal is emitted by the sonar and then after reflecting back from an object or surface, it can be detected by the sonar system. By knowing the speed of sound under the water and the signal travel time, an acoustic imaging can be acquired. Compared to cameras, acoustic sensors operate at much larger ranges and are less affected by dark environments of the underwater [31].

2.1.8 Passive Methods

Image-based modelling (IBM) is a widely used method for analysing geometric surfaces of architectural objects or for precise city modelling. IBM methods use 2D image measurements to acquire 3D object information through a mathematical model or they acquire 3D data using methods such as shape from shading. IBM methods are passive methods of optical 3D modelling.

The complete image-based 3D modelling method consists of several steps. Designing (which confirms the basic structure of the system and set the optical axes and determine the approximate number of images needed for data acquisition in addition to image resolution and on the other hand characterise camera calibration to optimise the accuracy), 3D measurements (by utilising developed algorithms to recover surface details of an object), structuring and modelling (surface reconstruction by generating surface triangular network), texturing and visualisation (by applying color images on triangular network form).

The main advantage of image based modelling is the inexpensive and portable sensor. In addition 3D information can be acquired regardless of the object size. Although generating a detailed 3D model from multiple images can be a difficult task, especially for large and complex objects where a wide baseline between the images is required and wrong integration could lead to deformed results. Photogrammetry and similar passive techniques are considered in IBM category [1].

2.1.8.1 Photogrammetry

Photogrammetry is the technique of model creation from pictures. The pictures can be conventional photochemical images or digital images. Photogrammetry can generate topographic maps or plans or can create a geometric model of an object by acquiring coordinates of separate points in a 3D coordinate system. Based on camera location, photogrammetry can be classified to aerial and close-range photogrammetry [32, 33].

In **aerial** photogrammetry the camera is installed under an aircraft and pointed vertically towards the ground. As aircraft flies, multiple images would be captured and then all would be processed and registered together for producing a topographic map of the area [34].

In **close-range** photogrammetry the camera is located close to the object and captured images would be used for 3D modelling and depth measurement of the object. Close range photogrammetry is used in architectural recording, artistic and engineering models measurements, deformation measurements, and moving process survey. As an example of the last application, photogrammetry is used in medical science and study of joints motions and movements in body [35, 36].

2.1.8.2 Shape from Shading

Shape-from-shading (SFS) is an optical passive method of object shape acquisition. SFS computes the 3D shape of an object through considering gradual variation of shading in one image of that object. Shading is one of the elements utilizes by human brain to recover the 3D shape. SFS utilizes the brightness of image pixels to compute the 3D shape of the object. Various equations and algorithms have been developed to improve this method. This method uses minimal data (a surface image) for 3D reconstruction or measurement of an object [37, 38].

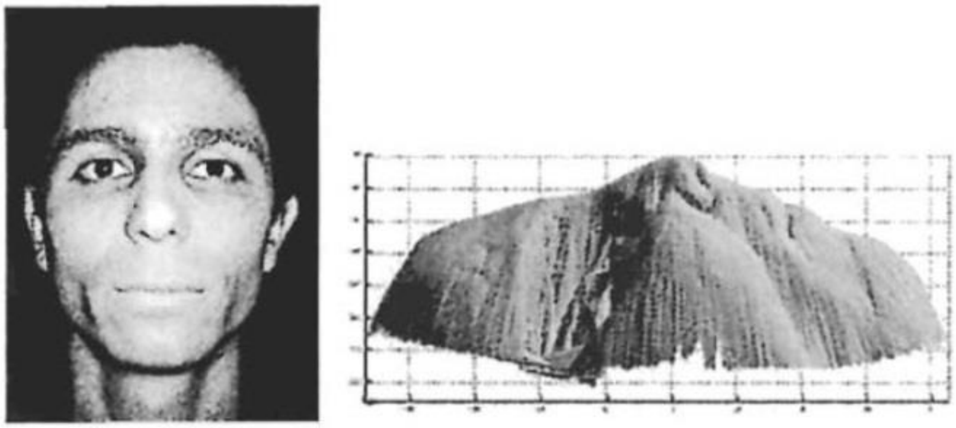

Figure 2-15: Real face image on left, and surface recovered from image by SFS algorithm on right [37]

2.1.8.3 Shape from Silhouettes

Illumination is one of the most critical factors which affect the process of shape recognition. The process can be drastically limited in absence of sufficient light. Therefore a method of modelling needless of light can be a good solution for this problem.

A silhouette is a type of image which shows the outline or boundary of an object and its interior is basically featureless and black in color. It happens as a result of projected light direction on the object where some areas cannot be illuminated due to occlusion. The shape from silhouette technique uses this characteristic of the silhouette to reconstruct the 3D shape of an object. First of all, the silhouettes of the real object would be captured from multiple views. Then, different volumetric cones are constructed using the focal point of the camera and the silhouette [39].

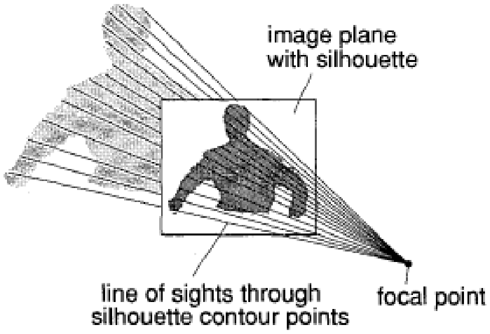

Figure 2-16: Construction of a volumetric cone [40]

Finally all volumetric cones from different viewpoints are integrated together and form the final 3D model. After editing and finalizing the 3D shape, the model can be textured using original images to have a realistic form. The accuracy of the method depends on the number and location of the cameras used to generate the input silhouettes [40].

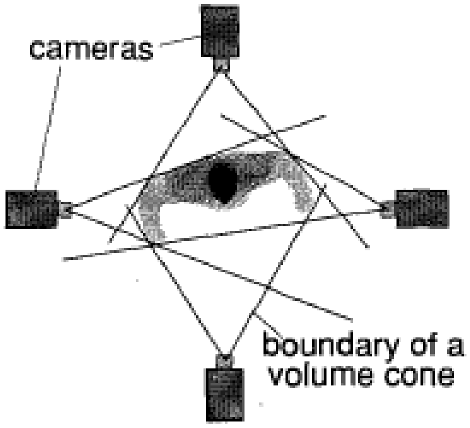

Figure 2-17: Top-view of the cone intersection [40]

2.1.9 A Comparison Between Range-based and Image-based Methods

A comparison between range-based and image- based modelling is reported in Böhler and Marbs [41]. In their experiments they used close-range photogrammetry besides various 3D scanning methods. They utilized three different scanners with structured light and triangulation methods with different range of scanning and precision. They worked on 3 different case-studies with different geometrical features. Criteria like quality of the results, amount of cost and time, required equipment and occurring problems were considered in their studies to compare two methods of 3D measurement and modelling. According to the results and conclusion, the question, which measurement technique is “better” than the other, cannot be answered. Each method has got its own pros and cons and therefore in many cases, a combination of different methods might be the best solution. Close-range photogrammetry would be the best solution where an object can be described by point or line structures but on the other hand there is no information between recorded lines and points. The main advantage of the photogrammetry compared to laser scanning is its inexpensive and portable sensor. In addition to that, photogrammetry needs shorter time for recording process, which is a great benefit in some projects, e.g. in heritage recording, with time limitation.

On the other hand, 3D scanning techniques give highly accurate information of the scanned object. They give better result in case of documenting very complex objects like sculptures with reliefs. In addition, the results of scanning projects can be visualized much well than the results of any other method.

In many applications, a single modelling method hardly can satisfy all the requirements. In many research projects (especially in cultural heritage projects) range-based and image-based methods have been combined to achieve the targets. Usually the basic shapes such as planar surfaces are determined by image-based methods while the detailed parts such as reliefs utilize range sensors [1, 42].

2.1.10 Conclusion

Various non-contact methods of 3D modelling and measurement were mentioned and studied in this report. In 3D modelling the main goal is producing a high quality and accurate model in a time and cost effective approach with the least human intervention, and many researches are implemented to achieve the target. It was clarified that creating an accurate 3D model of an object is still a difficult problem. Various methods have been developed during past few years for optimising shape acquisition methods. Due to each method cons and pros and because of significant specification of each application, there is no specific technique to be able to cover the modelling and measurement problems in all kind of application. Especially for complex projects with various objects, a combination of various sensors is in need to comply the requirements.

2.2 Problems with Different Scanning Methods

Almost all 3D scanning methods has some limitations and disadvantages. While contact scanners are in use, highly accurate 3D model of objects can be acquired but it happens slowly as the mobile arm of the system should move around for scanning various spots and by each contact the information of only one spot can be obtained. One of the other disadvantages of the contact scanners is that they are large and fixed and there is a maximum size limit for objects to be scanned and for scanning process the object must be transported to the scanner rather than vice versa.

In case of using optical scanners, surface properties of an object affects scanning result. The main requirement in 3D optical scanning is that the emitted light from the object surface (structured light or laser), must be visible by the scanner camera. This may not happen ideally based on surface properties. **Transparent** and **translucent** parts present a challenge in 3D scanning. In case of a transparent object almost no reflection happens and when scanning a translucent part, some light beams penetrate deeper in to the part and some of reflections occur from inside but not from the surface. Levoy, Marc, et al. faced problem in scanning translucent marble statue of David in the digital Michelangelo project. Marble is composed of densely packed transparent crystals which causes subsurface scattering when a laser light strikes its surface. As can be seen in Figure 2-18 the scattered light forms a volume under the surface and causes noisy result in scanning process. In this project two main issues helped to acquire higher quality scanning result of statues. Firstly the marbles were unpolished which caused diffused reflection of light. Secondly a layer of dust had covered the statue and changed the surface characteristic from shiny to opaque [42].

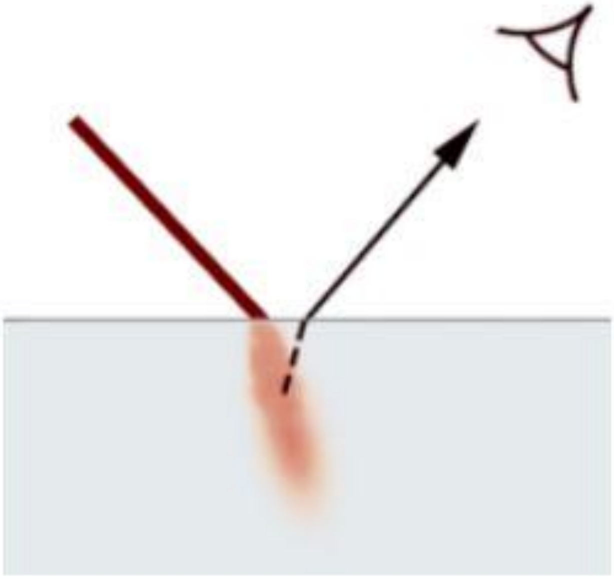

Figure 2-18: Subsurface scattering in a translucent object

Optical scanners have also difficulties in scanning **shiny** and **reflective** objects. In case of scanning a shiny object the reflection occurs in specular manner in a single direction and it doesn’t go toward the camera or receiving sensor. Also in case of scanning a shiny concave object some lights reflects on another part of the object and result in undesirable reflections and images. Furthermore in some cases, surface **color** present challenges for scanning process [43, 44].

2.3 Coating for 3D Scanning

3D scanning is extensively used in automotive industry for inspection and other purposes. In automotive industry and in general in manufacturing industry most parts have reflective surface finish mainly due to the machining process. In this situation, to improve the scanning result, the generated parts need to be coated to improve their visual appearance. Coating can help to improve the 3D scanning results for transparent and shiny objects. In most cases coating is done by means of an aerosol spray and due to the complexity of the object it is done manually [45]. Before scanning process of the manufactured part, preliminary preparation should be carried out to obtain better scanning result. Kuş, Abdil used calcite spray in his experiment to change the surface characteristic of the part from shiny to opaque (Figure 2-19). They mentioned that the coating thickness was about 10 to 20 µm [46]. Spraying a surface by aerosol covers the object pretty fast and change the surface properties to desired specifications for scanning process, although manual spray coating causes various problems such as material waste and over spraying. Aerosol sprays which are used for 3D scanning applications mostly contain matte white powder which dries off pretty fast and is removable from the surface. The coating thickness of an aerosol spray varies from 5 to 30 µm. Foot powder spray is the most common example which is used to provide a white dull coat on object surface.

Figure 2-19: Spraying the shiny automotive part before scanning [46]

The major drawback of aerosol spray coating is that there is no control over the thickness and uniformity of pigments exiting the spray can. Then in case of high accurate applications and for parts with small size and tiny features, aerosol spray coating can change and affect the part geometry and dimensions. As can be seen in Figure 2-20, after spray coating, the pigments agglomerate in the corner of the small groove on the object. The groove width is about 3mm and as the pigments go out of the nozzle divergently, there is no control over the coating material concentration and volume which cause increase in thickness and material round off at corners.

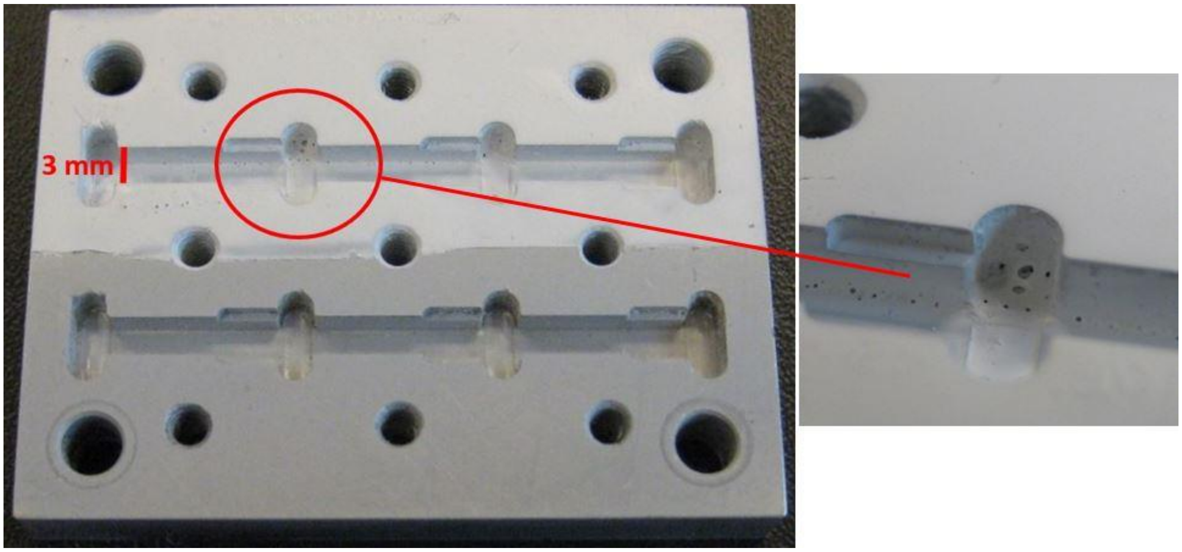

Figure 2-20: Coated part with an aerosol spray where pigments agglomerated in the groove and affected the geometry

2.4 Atomization-based Spray Methods

Nowadays atomization is widely in use in spray coating. Atomization can be defined as parsing of thin film of liquid into very tiny droplets in gas phase by overcoming the surface tension of the fluid. This can happen by destabilizing the jet by accelerating the liquid in to a nozzle or with the help of centrifugal or electrostatic forces. Droplets range in size from submicron to several hundred microns in diameter. The spraying functionality of atomizers depends on liquid properties such as viscosity and surface tension [47]. Atomizers classify in various types mainly according to their energy sources. A summary of some types of atomizer is provided in this section.

2.4.1 Pressure Jet Atomization

Pressure jet is the simplest form of atomizer which usually consists of an orifice and is widely use in diesel engines for fuel injection. Plain orifice, pressure swirl, and square sprays are typical examples of pressure atomizers. Plain orifice is the simplest type of this kind. The liquid is accelerated through a nozzle, forms a liquid jet and then breaks up to form droplets. Usually applying high pressure which then converts in to kinetic energy (increasing the velocity) cause the liquid disintegration [47, 48].

2.4.2 Ultrasonic Atomization Spray Coating

If atomization happens on a vibrant surface, it is called ultrasonic atomization. This method of spray deposition has couple of strengths over the conventional spraying methods. In this method of spraying, very tiny droplets of the solution can cover the target surface in a pretty uniform way and make a thin layer over the object.

Basically an ultrasonic spray coating system converts electrical energy to high frequency mechanical energy in the form of vibration which then transfers this vibration to the liquid surface and causes atomization of the liquid. In ultrasonic spray coating method, the coating solution is broke down to fog of droplets first and then with the help of stream of air is deposited on the target surface. An ultrasonic atomization coating system has two main characteristics. It can generate droplets in very small size and then it can gently deposit the droplets on a specific surface with minimum bounce back. This leads to reduction of coating material as decreases the material wasting [49].

Piezo atomizer is a type of atomizer which can be used in ultrasonic coating system. In this system the main part of an ultrasonic spray is a piezoelectric transducer. Piezo as a Greek word means “to press”. In piezoelectric effect, a potential creates in the material when it is squeezed. On the other hand, when electric potential applies on a piezoelectric material, it causes expansion. By alternately changing the electric potential, the material rapidly compresses and expands and causes a mechanical vibration which simply leads to conversion of electrical energy to mechanical vibration without using any electric motor. This vibration at ultrasonic frequencies produces short wavelengths necessary for fine atomization [47]. Based on the specified information, the droplet size (diameter) of an ultrasonic spray depends on the surface tension, density of fluid, and applied frequency [50].

Two major hypotheses have been proposed for liquid disintegration during the ultrasonic atomization; capillary wave and cavitation.

Capillary wave is a wave which travels through the phase boundary of a liquid. In this method when a beam of ultrasound with enough power passes through a liquid and directed to the air, atomization happens. In this process capillary waves are the source of vibration on the liquid. By increasing the vibration and subsequently the wave's size, the distortion happens in the liquid in a shape of wave and the wave gets larger with higher peaks gradually. Then based on the physio-chemical properties of the coating material, tiny droplets split from the solution on peaks of the wave and eject upward where then can be inserted in to the gas stream of the spray and deposited on the surface from the spray head or integrated nozzle.

Cavitation can be defined as the generation, growth, and disintegration of cavities in a liquid. In cavitation hypothesis of ultrasonic atomization, when the liquid film gets sonicated, tiny bubbles are produce in the liquid film. These tiny bubbles give minimum thickness to the liquid film in some areas which then by getting excited due to the vibration, the cavities fall apart and cause disintegration in liquid and ejection of tiny droplets [51]. As it was mentioned before, the droplet size in ultrasonic atomization depends on material properties of the liquid such as viscosity or surface tension, ultrasonic parameters such as applied frequency, and operating parameters such as liquid flow rate.

2.4.3 Collison Nebulizer

Collison nebulizer or atomizer is also used to generate mist of atomized droplets from a liquid supply. This nebulizer is consists of a (usually) glass jar, a head part with inlet and outlet port for compressed air and atomized particles, and an inner tube which has a nebulizing head at its end. As can be seen in Figure 2-21, the jet 1 is connected to the spray nozzle 2. The lower part of the nebulizing head is located in to the liquid and must be covered with the solution during the spray procedure. When compressed air is blown in the nozzle from the jet, a drop in static pressure sucks fluid up through the tube 3, from the liquid reservoir. The pressure drop can be explained with Bernoulli's principle. Based on that, an increase in the speed of the fluid leads to decrease in pressure. This pressure drop causes the liquid to be sucked up from the jar through the tube towards the nozzle. The liquid then breaks up in to small droplets in various sizes by the air jet. Then the droplets are impacted to the jar wall through the nozzle (at 4). This impact separates the larger droplets from the tiny ones. The larger and heavier droplets get back to the solution and very tiny droplets go in to the stream of the air and exit through the outlet tube of the atomizer [52].

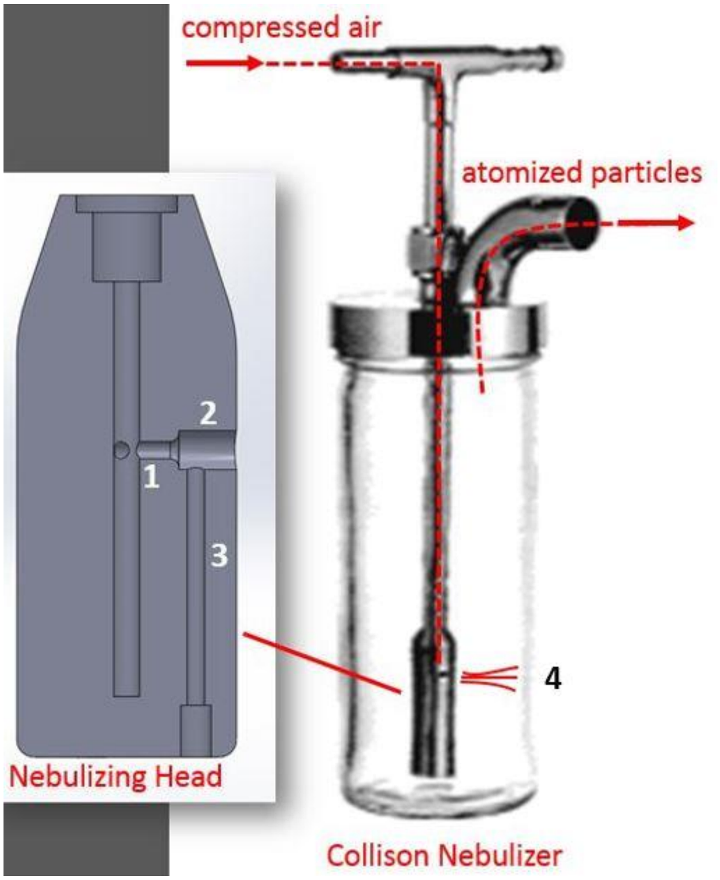

Figure 2-21: Collison Nebulizer

2.4.4 Pressure Spray

Pressure spray or aerosol spray is a dispensing system which creates fine liquid droplets from a product fluid inside the can. In this conventional method of spray the product exists in a can under a specific pressure. Erik Rothiem, a Norwegian inventor, designed the first pressure spray. Although there have been various improvement in the pressure spray system, the main concept has stayed the same as the first design. A spray can usually contains a product and a propellant. Propellant is the material which in specific conditions inserted in to the spray can and works as the stimulator to force out the product material. There are two major spray can methods. In the simpler method, the propellant exists in gas phase. The can is sealed after filling with specific amount of the product in liquid shape.

Then the gas propellant pumped with high pressure in to the spray can. The high pressure gas applies downward force over the liquid product. There is a tube from bottom of the can which connects to the spray cap or nozzle. A valve exists in the spray cap which is pushed up with a force from a spring which helps to block the pathway of the product inside the can. When the valve is pushed down, it opens the pathway and the propellant forces the product out through the tube. The narrow nozzle which is located at the end of the valve atomizes the product in to tiny droplets and disperses them out.

The liquefied gas propellant can also be used in pressure spray can. In this method the propellant stays in liquid shape beside the product inside the can due to the high pressure over it. In this system when the valve is pushed down, the pressure inside the can drops down, causes a part of liquefied gas propellant boils and change in to the gas. This pressured gas then pushes the liquid, which consists of product and propellant, out of the spray can. When the liquid is passing through the tube to the nozzle, the liquid propellant changes to the gas instantly, this helps to atomize the liquid product.

Chapter 3 : Development of Spray Coating System

For solving the problem of difficult objects in scanning (e.g. shiny or transparent), a newly designed spray coating system was developed and evaluated in various experiments. The spray coating system consists of an atomizer with a newly developed nozzle. Knowing the advantages of an atomizer, a nozzle was integrated into it to control the droplets concentration and increase the coating quality.

The idea arose from experiments on applying an atomization-based cutting fluid in micromachining by Jun, Martin BG, et al. [53, 54]. Figure 3-1 shows the atomization-based cutting fluid system.

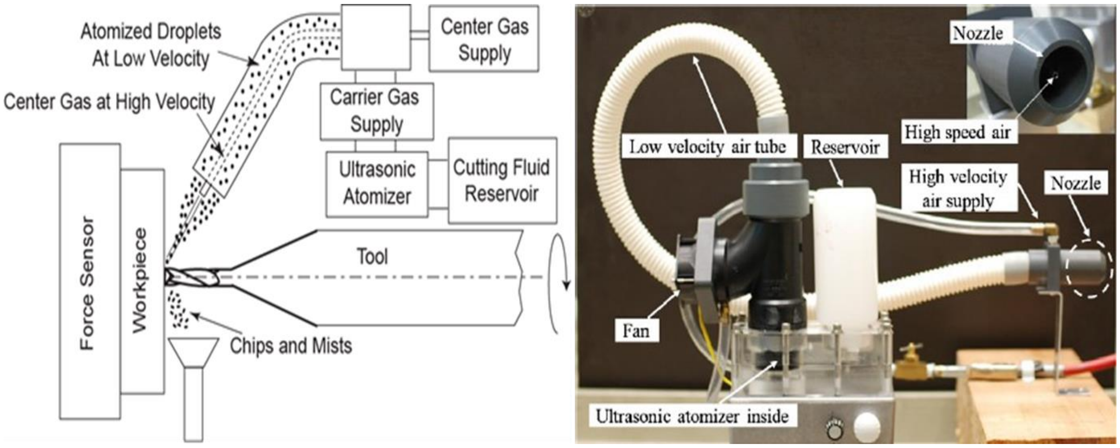

Figure 3-1: Design of an atomization-based cutting fluid application system [54]

In a series of experiments the authors tried to atomize cutting fluid for lubrication and cooling purpose in the area between the tool and the part in micromachining. Due to the very small size of tools in micromachining, the conventional methods of coolant dispersion might not be suitable for lubrication and cooling purposes. Thus, the atomization-based spray cooling system was tested to improve the results. The atomized droplets could access the cutting zone easily and absorb the heat of the machining area and remove it through evaporation. Coolant atomization was done in micromachining for increasing the tool life and the quality of the machined surface. The results showed a significant improvement from the conventional spray methods. The newly designed system led to lower cutting force and better tool life.

To use this system in the scanning process a new nozzle was designed to be integrated into the atomizer. The main criteria for the design were quality improvement and ease of use of the nozzle. Nowadays 3D scanners are quite simple to use. The geometric data of a part can be acquired with several clicks and the generated mesh file is converted to a surface or solid model quickly. Therefore the coating process should be as simple as the scanning process. For that, it is desirable to use a portable, hand-held nozzle for coating process.

The hand-held nozzle is designed for use with the atomization coating system. The full system consists of an atomization device, velocity system, and the spray nozzle. The atomizer atomizes the solution into tiny droplets. Then the atomized particles are moved to the nozzle with the help of carrier gas. The nozzle then helps to have more control on the spraying and dispersion process by concentrating the droplets on a specific area.

A collison nebulizer was used as the atomizer. An ultrasonic atomizer can also be used with the system, but with the proposed coating solution the nebulizer showed better results by generating bigger volume of droplets compared to the ultrasonic atomizer. Besides, the nebulizer has a very simple structure and does not require any source of electricity. Therefore it can be a suitable part to be integrated into this portable coating system.

3.1. Nozzle Preliminary Design

For the new nozzle design, the features of the nozzle of the atomization-based cutting fluid application system were taken into consideration. The full coating system consists of an atomizer, the delivery system, and the spraying nozzle. The nozzle itself consists of an inlet pipe for atomized droplets to enter, a hollow cylinder, a honeycomb structure, a triggering knob (connected to a three-way hub), an outlet tube for droplets to exit, and a high velocity air jet pipe. Figure 3-2 shows the nozzle preliminary design.

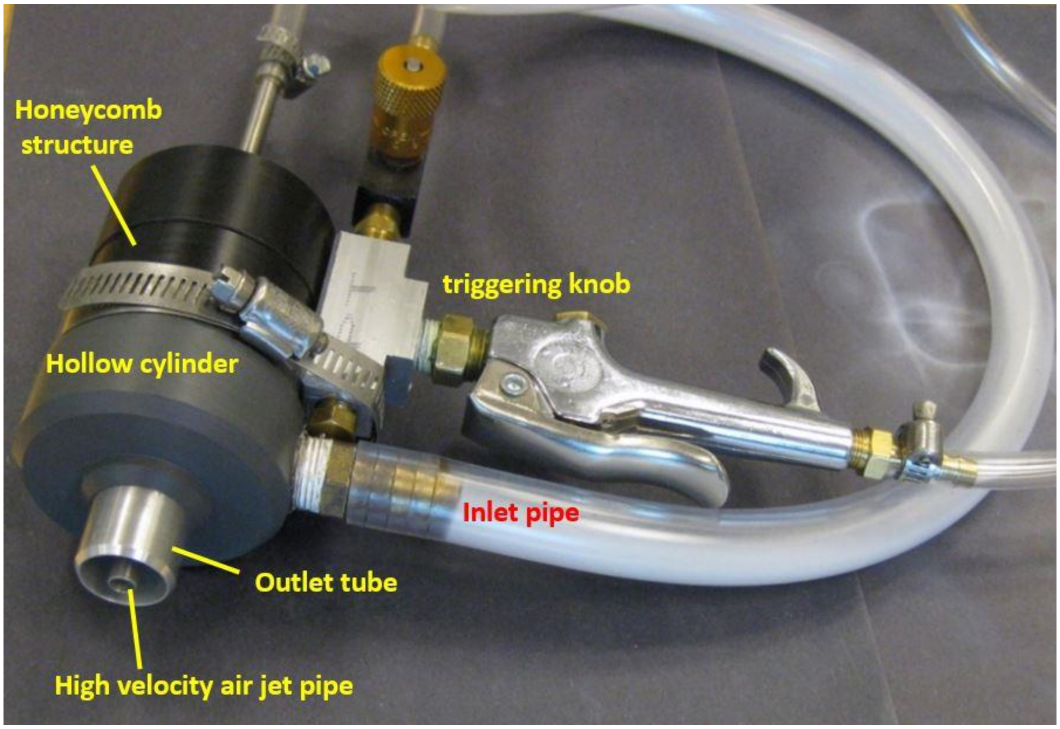

Figure 3-2: Nozzle preliminary design

The whole process can be summarized as follow. Firstly the coating solution is atomized into tiny particles. Then the atomized droplets are conveyed to the nozzle at appropriately low velocity to avoid condensation of droplets within the hollow cylinder of the nozzle. Inside the hollow cylinder, first the droplets are passed through a honeycomb structure, at 1 (Figure 3-3), which reduces the flow turbulence, then the particles enter the outlet tube at 2. Once the droplets are out of the tube, the trigger knob is pressurized, letting high velocity air into the middle tube, which accelerates and focuses the droplets at the exit for proper impingement and dispersion over the target surface.

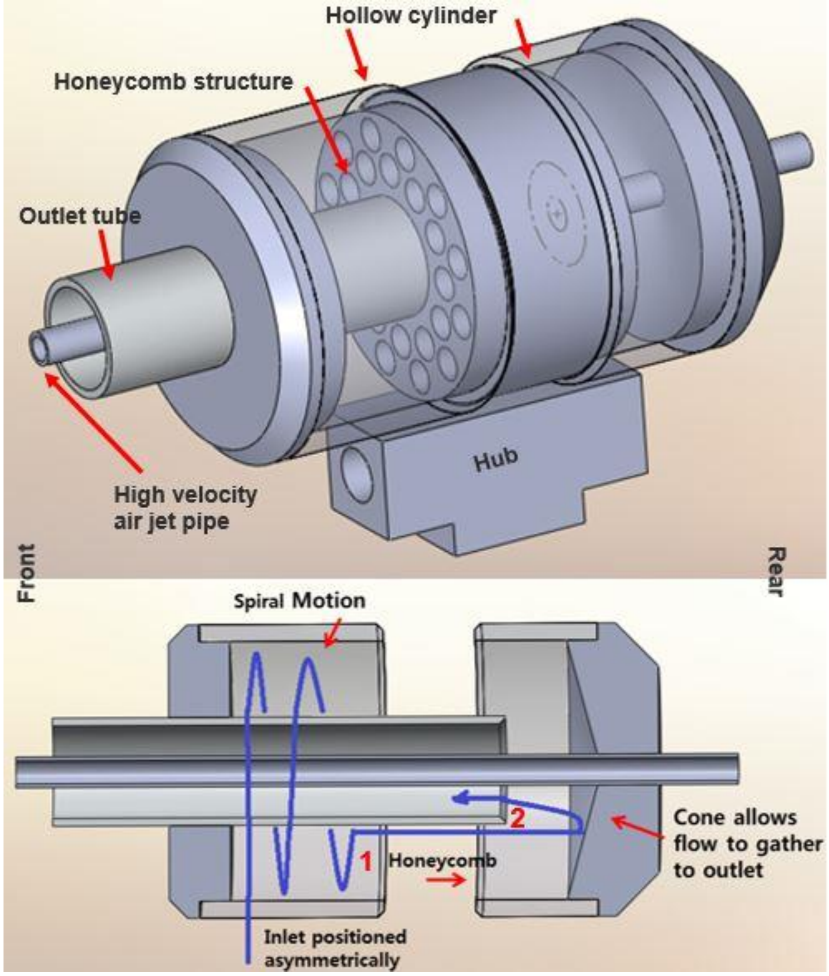

Figure 3-3: Nozzle preliminary model

To start the design, the hollow cylinder, the honeycomb structure, and a three-way hub were designed and manufactured. The inlet tube was located asymmetrically in the front part of the hollow cylinder to give a spiral motion to the fluid around the outlet pipe until the droplets reach the honeycomb structure. This spiral motion has a centrifuge effect to sort the droplets by size. The honeycomb structure stabilizes the flow and decreases the turbulence. The rear part of the hollow cylinder has a cone shape which directs the droplets into the outlet pipe. The cylinder and the honeycomb structure were pressure fitted as an assembly and a hose clamp was used to mate the hub and the nozzle.

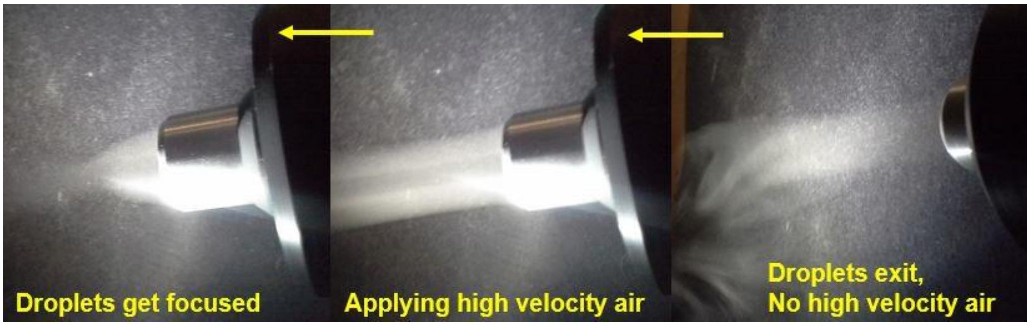

Figure 3-4: High velocity air at the exit focuses the droplets (read right to left)

3.2. Hand-held Nozzle Design

The preliminary design of the nozzle showed satisfactory result in producing a uniform coating of micro-sized particles. Therefore the main features of the preliminary design such as the hollow cylinder and honeycomb structure were used in the nozzle. Previous experiments had already shown that better layers of coating can be applied if the nozzle consists of a hollow cylinder with a honeycomb structure inside. The critical design feature of the hollow cylinder is the asymmetric entrance and axisymmetric exit because this geometry induces a fluid motion that first sorts the particles and then reduces the turbulent disturbances at the tip of the nozzle (Figure 3-5).

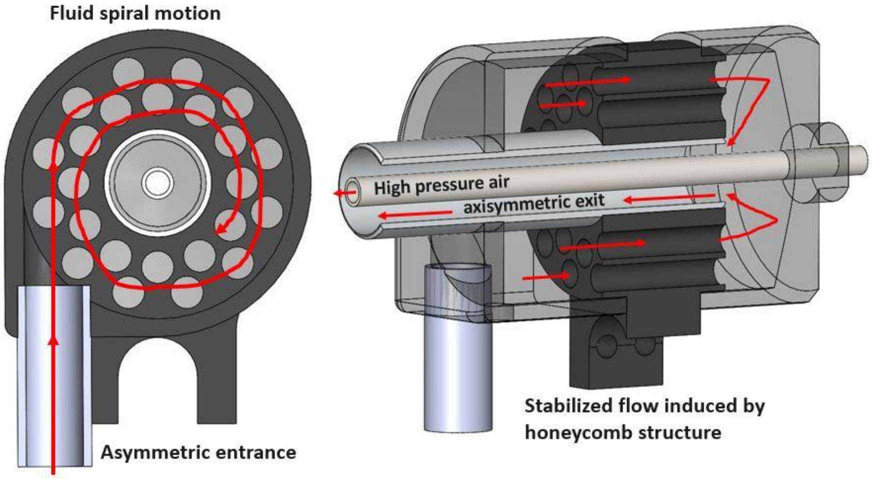

Figure 3-5: Nozzle ergonomic model

The first improvement for the new design was to optimize the nozzle parts assembly. In the previous design the three-way hub was mated to the nozzle only by a hose clamp. Secondly, an attempt was made to design the nozzle ergonomically, to make it more comfortable for a human to operate. Considering these two issues, the three-way hub and the blowing trigger were replaced by a blow gun. The blow gun can provide stronger support against nozzle weight. It also eases nozzle holding by hand and eases the coating process for the operator (Figure 3-6).

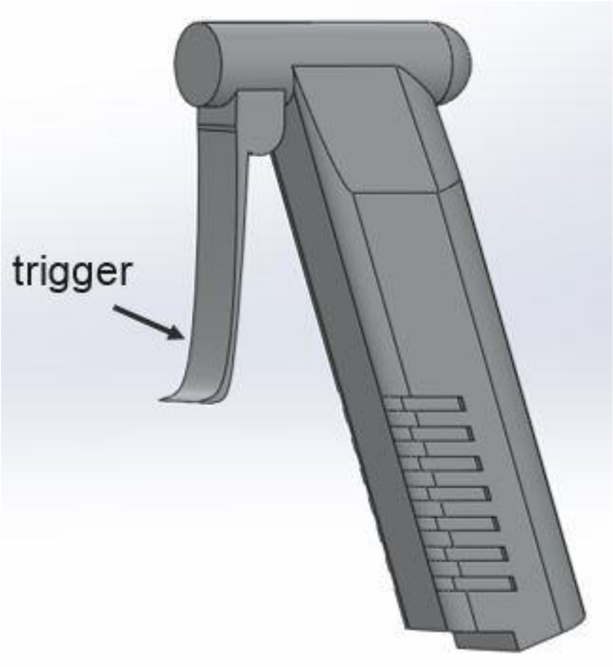

Figure 3-6: Blow gun

After adding the blow gun, the honeycomb structure was modified by adding an extrusion to it. The upper part of the nozzle can be assembled from this section to the blow gun with the help of set screws which also increases the stability of the whole system. The honeycomb structure with the extrusion part can be seen in Figure 3-7.

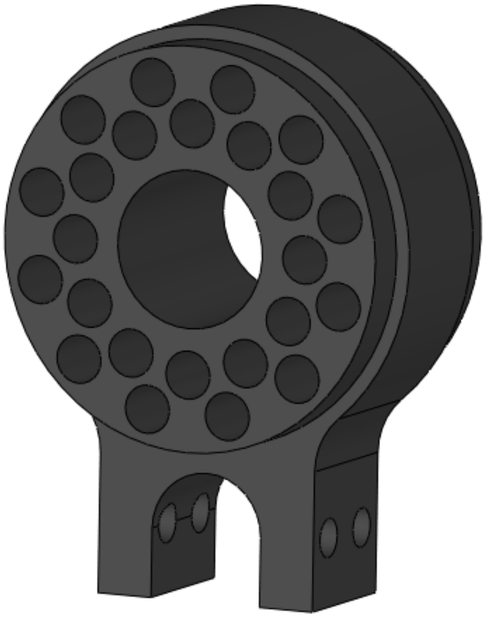

Figure 3-7: Honeycomb structure

In the design of the new hollow cylinder, two major changes were considered. First of all, a drain outlet was added to the structure to exit any probable condensation of the solution residues. Moreover, the particles inlet was moved even farther away from the axis to optimize the spiral motion of the flow. Both added features are shown in Figure 3-8.

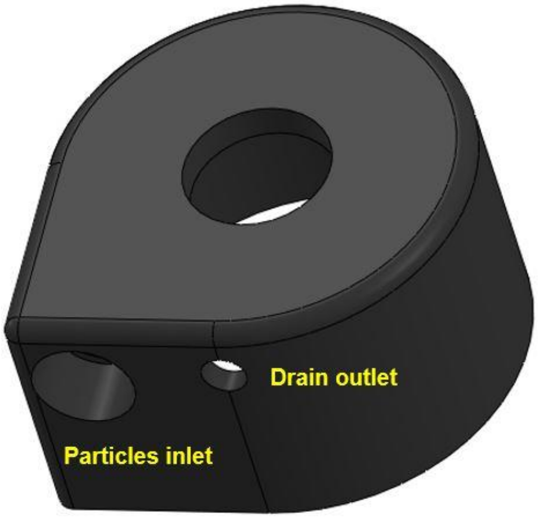

Figure 3-8: Hollow cylinder, front section

The same design was used for the rear part of the hollow cylinder with the cone shape segment, and then the honeycomb structure and the hollow cylinder were pressure fitted together to shape the assembly of the nozzle upper part (Figure 3-9).

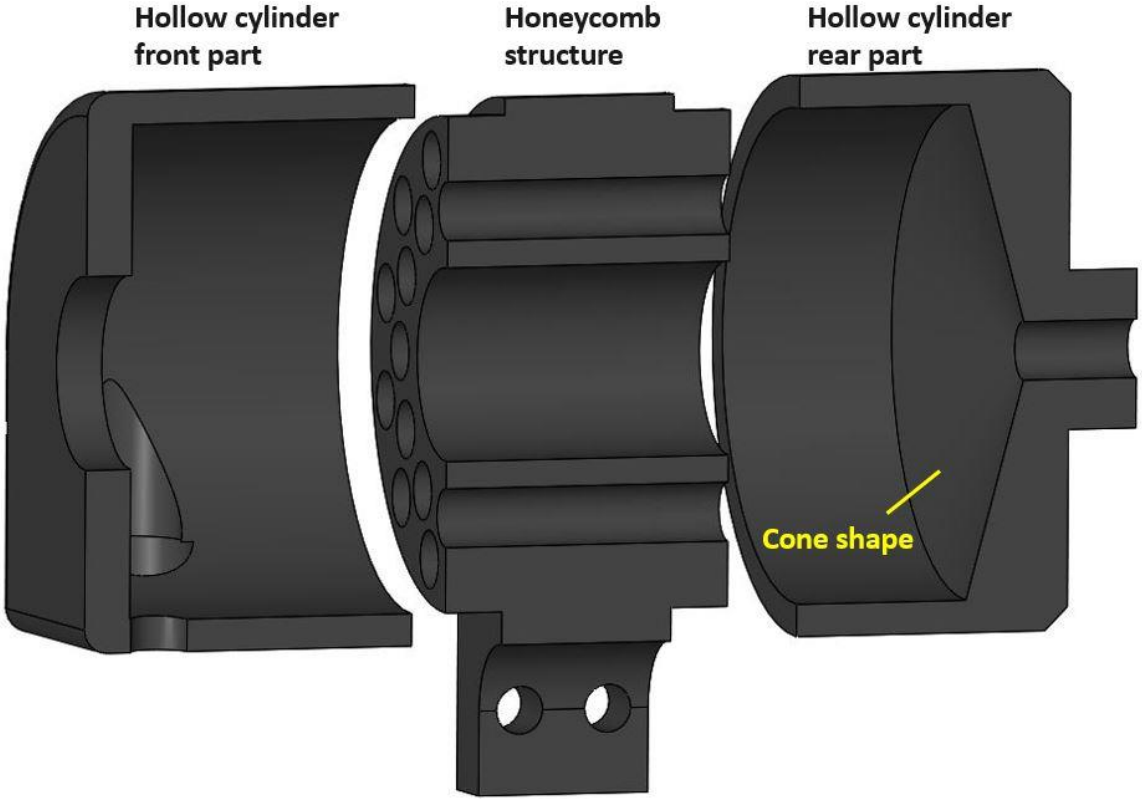

Figure 3-9: Cross section of the exploded view for the nuzzle upper part

The honeycomb structure and the hollow cylinder were machined out of PVC plastic. The drain and particles inlets were made out of aluminum, and stainless steel was used for the high velocity tube.

Set screws were used to hold the nozzle core and the blow gun. The screw forces were enough to hold the nozzle in place without any movement. To give a better understanding of the final design, the full assembly picture is shown in Figure 3-10.

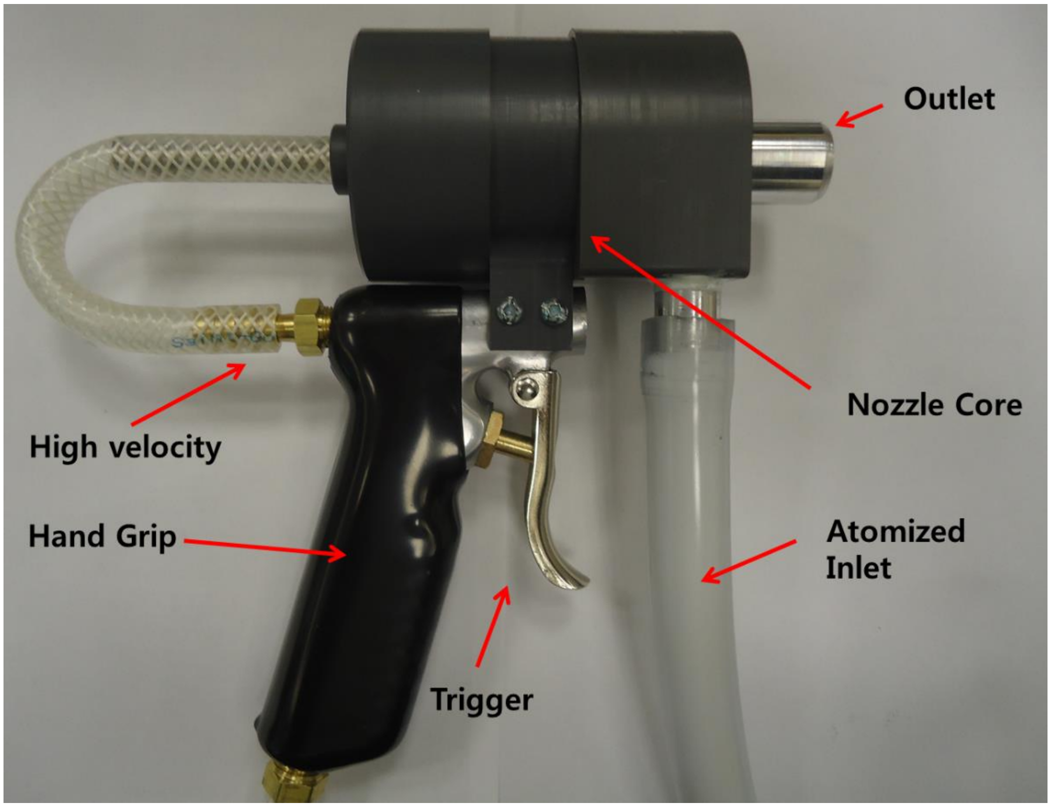

Figure 3-10: Assembled nozzle

Chapter 4 : Evaluation of Spray Coating with Different Scanning Methods

To study the effectiveness of the newly designed spray coating system for the 3D scanning process, various experiments were done on three different basic samples. Each sample had specific surface characteristics which impede the scanning process. Through these sets of experiments the coating quality was also investigated. The uniformity and thickness of coating were major criteria for quality evaluation. Various microscope glass slides were tested first as fully transparent objects. It is almost impossible to scan a transparent or translucent object as the light passes through or penetrates into objects and causes no light reflection or subsurface scattering. As the second sample, various gauge blocks with mirror polished surfaces were used as highly reflective objects. In case of shiny or reflective objects, light is reflected from the surface in a specular way rather than diffused reflection and causes problem in scanning results. As the last part, various color samples were used to study the effect of surface color on the scanning results. Basically, optical scanners have problems in scanning dark objects as dark colors absorb light instead of reflecting it.

4.1 Equipment and Material Used For Experiments

4.1.1 3D Scanners

Two different active optical scanners were used to study the efficiency of the developed spray coating system on 3D scanning by capturing a 3D model of coated objects. An “HDI Blitz” structured-light 3D scanner by “LMI Technologies” with accuracy of 120 microns and a laser scanner by “David” with accuracy of 200 microns were utilized to study and compare the results in this stage of the experiment.

4.1.2 Target Objects

As mentioned before, microscope glass slides (as transparent samples), gauge blocks (as reflective and shiny samples), and semi-gloss colour samples were used in this part of the experiment as target objects for scanning. Based on previous studies transparency, reflectivity, and dark colour of a surface are three major traits which cause problems in optical 3D scanning processes.

4.1.3 Coating Material

Titanium dioxide white pigments were used as the coating material. Optical properties of titanium dioxide make it the best coating pigment for thin layer coating. Titanium dioxide increases the “hiding power”. Hiding power is an optical property which is used to describe the light-scattering efficiency of a pigment (especially white) and is the ability of a paint to obscure the surface upon which it is applied. The major specification which increases the hiding power is a high refractive index of the pigment. When the light hits a surface with high refractive index, it is bent toward a line perpendicular to the surface. Figure 4-1 shows that a pigment with higher refractive index can bend and scatter light more than a pigment with lower refractive index and provide more opacity and hiding power to the surface.

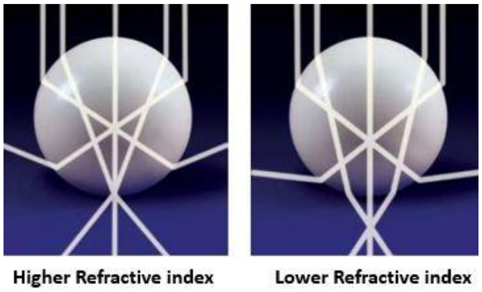

Figure 4-1: Pigments with high and low refractive index

Titanium dioxide has quite high refractive index which ensures strong light scattering from a surface. This also makes it a good pigment for thin layer coating.

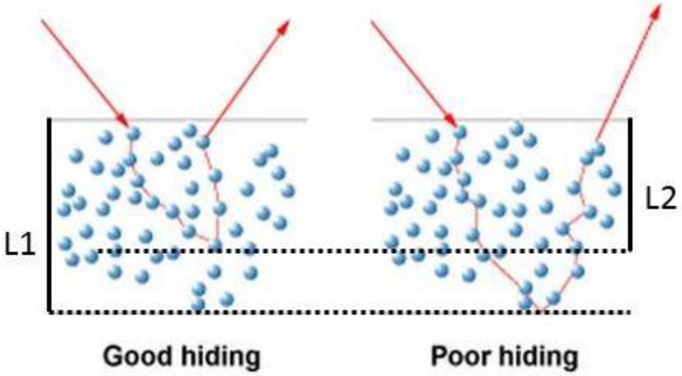

Figure 4-2: Higher refractive index pigments can scatter light completely with less thickness

Comparing the pigments with higher (left) and lower (right) refractive index in Figure 4-2, they both can scatter light completely from the surface when the coating thickness is L1, while by decreasing the coating thickness to L2, the lower refractive index pigments cannot scatter light well and decrease the hiding power and opacity of the surface.

4.1.4 Data Processing

A zeta-20 optical profilometer was used to study the thickness and uniformity of coating. The profilometer can be used for thickness and roughness measurement of the coated surface. It can scan the sample over a user-specified vertical range. At each Z position, the profilometer records the X and Y coordinates and uses the information to generate a 3D image of the surface. The profilometer provided 3D imaging and metrology features for the experiment.

4.2. Thickness Measurement

4.2.1 Atomization-based Spray System, Thickness Measurement

Coating thickness was measured based on the number of passes and layers of coating on the surface. For this purpose various glass slides with 1 to 10 layers of coating were used for thickness measurement (Figure 4-3).

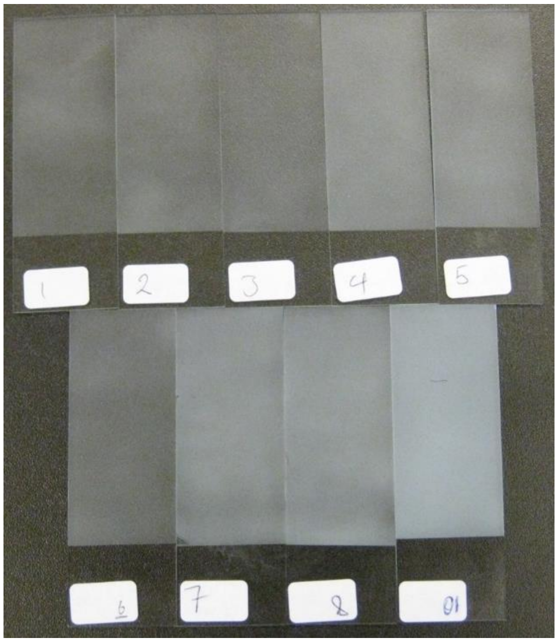

Figure 4-3 Coated glass slides

All coatings were done manually (not automatically) to consider the spraying situation in an industrial setting in which a person who does not do coating as his/her daily job might be doing the spraying! In this case various errors may occur during the spraying process especially when applying the fourth or fifth layers or higher. These errors were considered negligible in this experiment. Basically when applying more layers of coating on a surface, the object gets the color of pigment to itself and beyond a certain point, the need for spraying more layers cannot be recognized by human eyes, but it can be distinguished by equipment such as surface profilometers or 3D scanners. This can be a main source of errors as the operator may add more pigment on a specific area or less on the other side unintentionally. All slides were studied by means of the profilometer. Figure 4-4 shows the uniformity of a coated slide with 1 layer of coating with magnifications of 5, 20, 50, and 100.

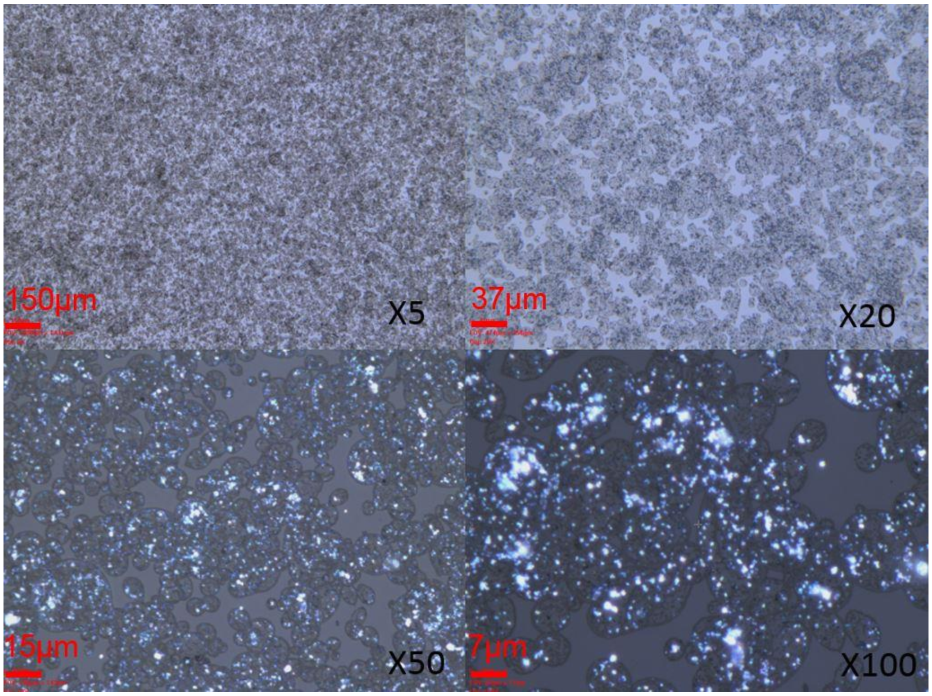

Figure 4-4: Images of 1 layer coating with various magnifications

The coating thickness increases respectively by applying more layers but due to the aforementioned error in manual spraying, this thickness increase is not exactly equal to the amount of one individual manual coating pass multiplied by the number of passes. Based on the acquired data from the profilometer and with the specific pigment used for the experiment, each layer has an approximate thickness of 75 to 100 nanometers. The pigment particle size is one of the major factors which determine the coating thickness. Figure 4-5 shows the thickness of the coating for various layers of coating on different slides.

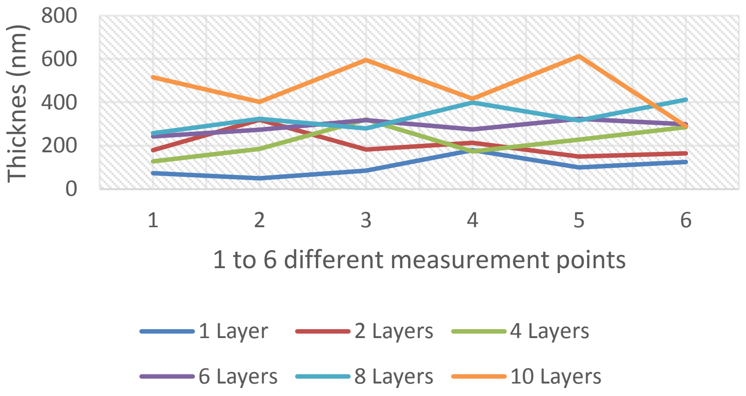

Figure 4-5: Thickness measurement results

It should be kept in mind that the thickness varies based on particle size, time of concentrating the nozzle on a specific area, and coating speed. Then the presented data is valid for this experiment. Figure 4-6 shows the average coating thickness of this experiment.

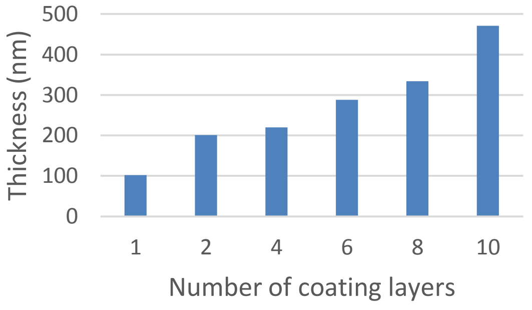

Figure 4-6: Average coating thickness based on number of layers

In Figure 4-7 slides with 1, 4, and 10 layers of coating are compared. The figure provides X5 and X100 magnification images of the coated slides. X100 magnification image of 1 layer coating shows that spraying covers the surface but some areas stay uncoated. A similar image for 4 layers of coating shows that applying more layers up to 4 fills those uncoated areas but does not increase the thickness significantly. Finally the X100 magnification image of 10 layers of coating demonstrates that the slide is covered completely by the coating material. In this image both clear and opaque pigments can be seen. This shows that more layers, up to 10, can cover the entire surface and can add more pigments over the previous layer. The clarity and opacity of pigments are due to their different heights over the surface.

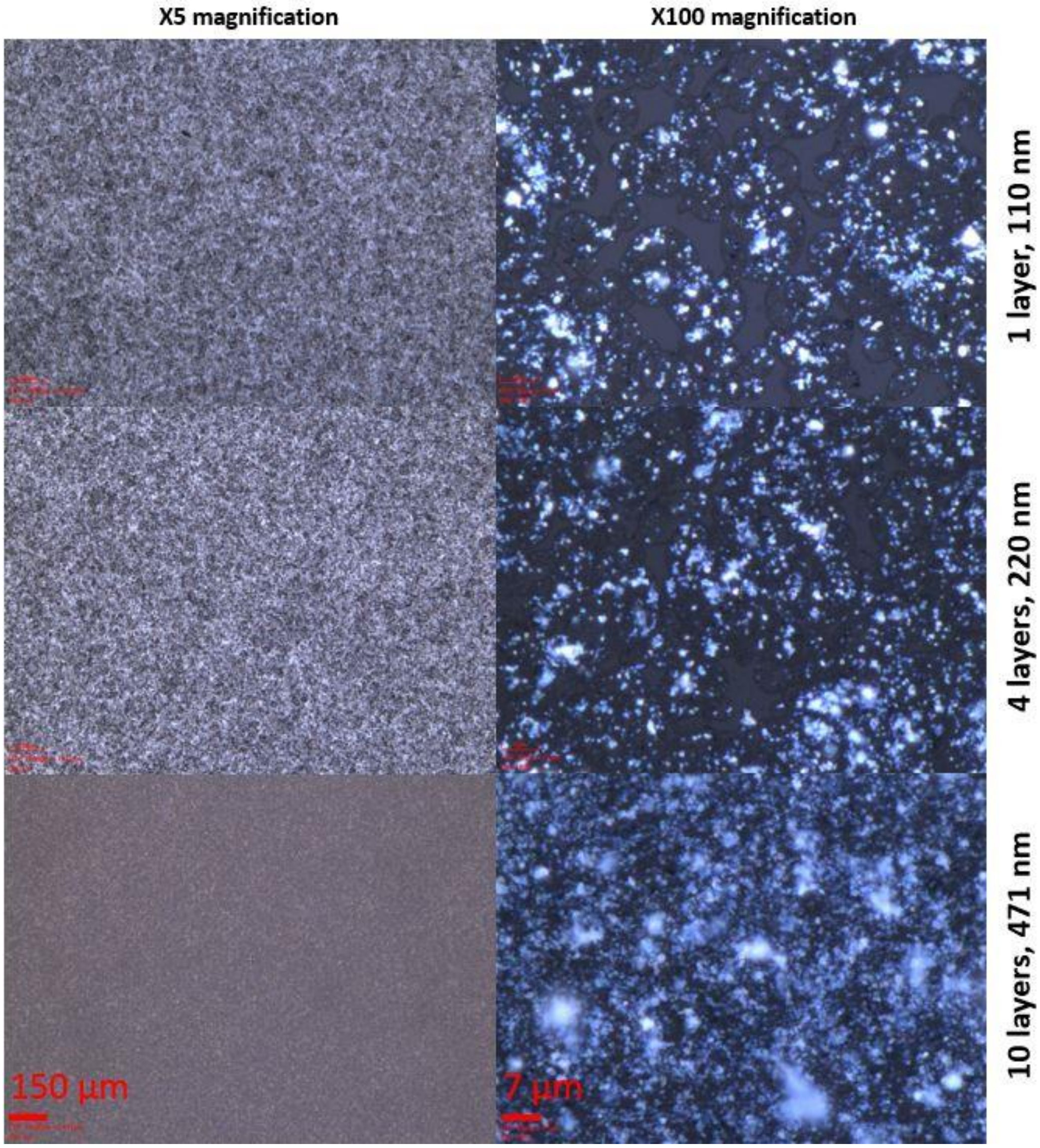

Figure 4-7: X5 and X100 magnification images of 1, 4, and 10 layers of coating

4.2.2 Aerosol Spray, Thickness Measurement

Coating the surface with proper specifications is the easiest approach to solve the problem of difficult surfaces in optical 3D scanning. The spray coating is usually done by means of an aerosol spray. This is quite fast and effective but the issues are the coating thickness and material concentration.

To measure the approximate thickness of an aerosol spray coating, a new glass slide was coated by an aerosol spray with one layer and the thickness was measured with the help of the surface profilometer. An effort was made to minimize the amount of material used over the slide. Figure 4-8 compares the slide coated with 1 layer of aerosol spray and the slide coated with 10 layers of atomization-based spray. The slides were studied by a surface profilometer and the result showed over 10 micron thickness for the aerosol spray coating, which is almost 20 times bigger than the thickest layer applied with the atomization-based spray in this experiment (10 layers). Thus the atomization-based spray produced by the design changes the geometry of the object to a lesser extent as desired.

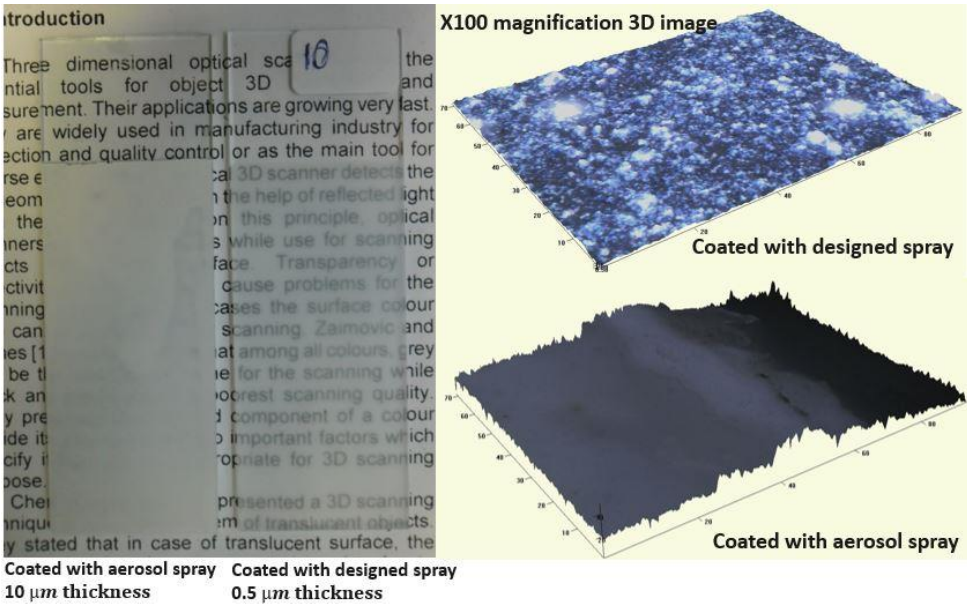

Figure 4-8: Comparison results of aerosol and atomization-based spraying

4.3. Scanning Results for Coated Transparent and Reflective Objects

To evaluate the efficiency of the designed spray coating system on 3D scanning of transparent samples, the coated slides which were used for the thickness measurements were scanned as target objects. The samples were scanned by a structured-light and laser scanner separately.

4.3.1 Structured-light Scanner Results for Coated Transparent Samples

Coated glass slides were scanned first by means of a structured-light scanner. Various slides were coated by the newly designed spray with almost 50 to 500 nanometre thickness, and one slide was coated with a spray can to a thickness of 10 microns (Figure 4-9).

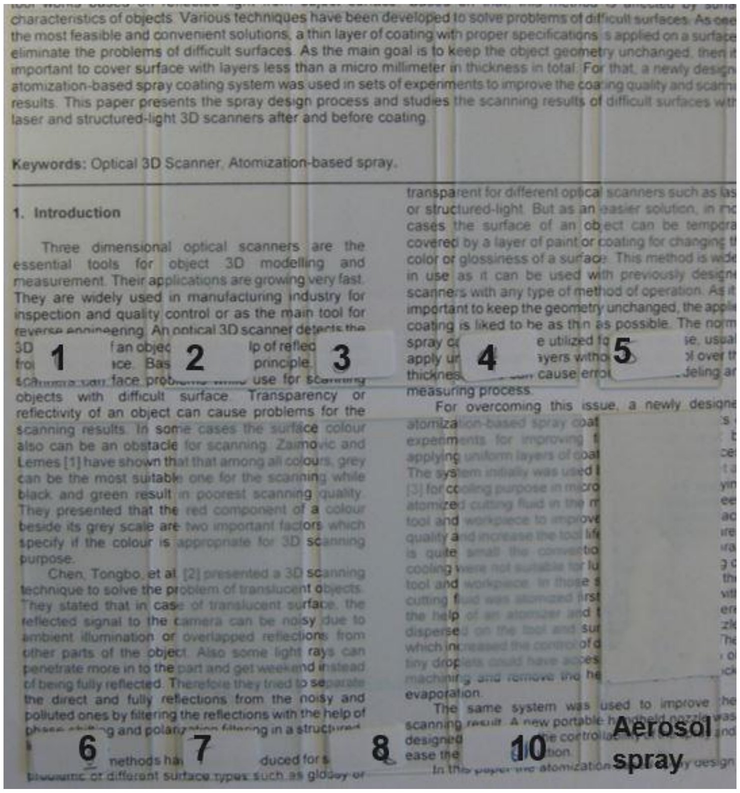

Figure 4-9: Coated glass slides

It is almost impossible to scan a glass slide as a transparent object and no data can be obtained from its surface. As it can be seen in Figure 4-10, the scanning result were greatly improved highly by applying 1 layer of coating but the quality was still insufficient. Slides with thicker coating were tested one by one and the scanning results improved respectively by increasing the coating thickness. The best result was acquired for slides with 10 layers of coating, which showed a thickness of nearly 500 nanometres. Also, as can be seen in Figure 4-10, the scanning result of the slide coated by the aerosol spray is better in uniformity and shows a higher quality model of the sample, although compared with the other slides, the coating is at least 20 times thicker and it has larger variations in thickness.

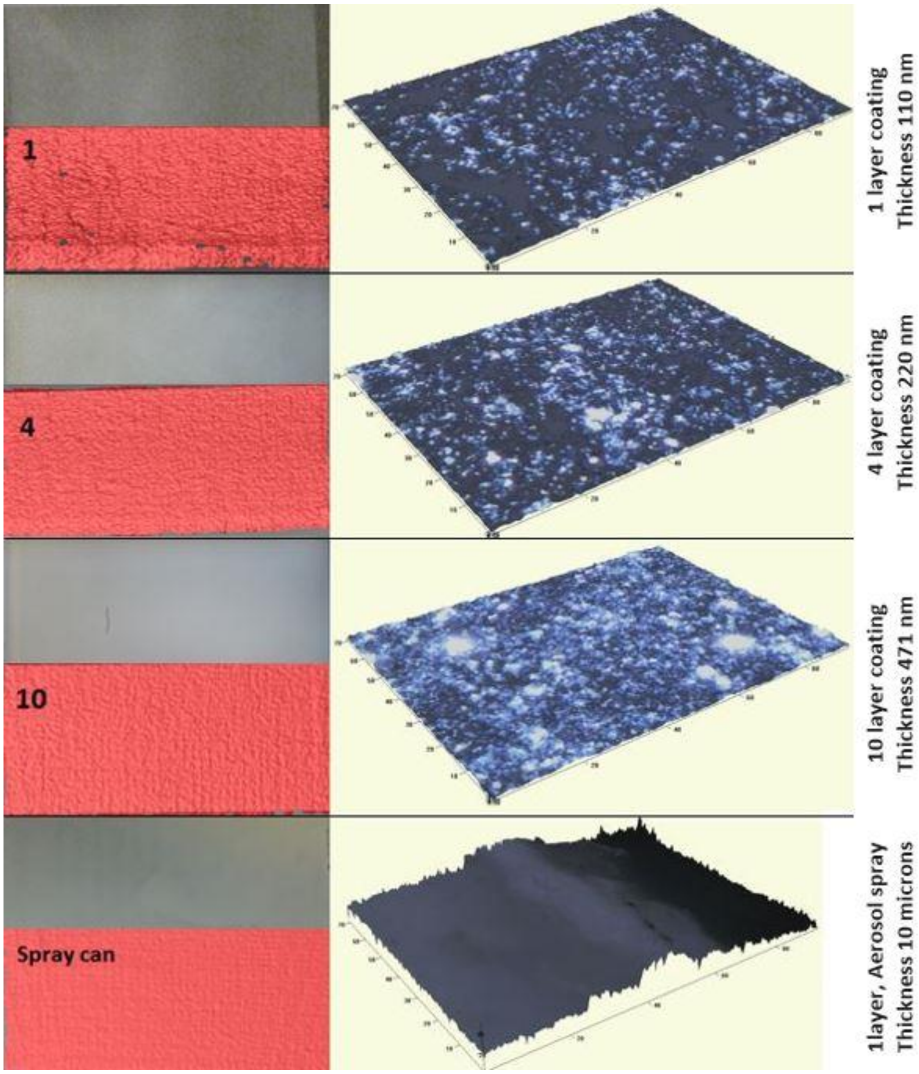

Figure 4-10: Structured light scanning results of coated slides (left column), X100 magnification 3D image of slides by profilometer (right column)

Based on the acquired data from the scanner software for this specific geometry, for each of the scanned slides, around 50,000 vertices were scanned and this number didn’t change with increasing the coating thickness. In other words from the very beginning, even with one layer of coating, the number of scanned points increased drastically and this number stayed constant for other slides with thicker coating, although the scanning quality was increased by applying more layers of coating over the surface.

4.3.2 Laser Scanner Results for Transparent Samples

Same transparent samples (coated glass slides) were scanned by means of a laser scanner. Figure 4-11 shows the final scanning results of the transparent samples.

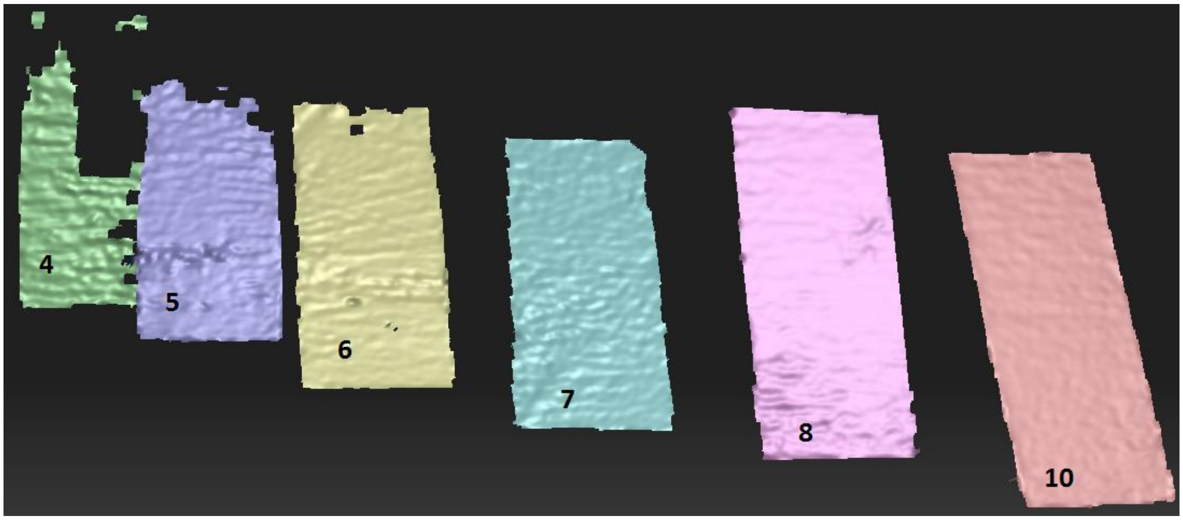

Figure 4-11: Laser scanning results of glass slides with 1 to 10 layers of coating with thickness of nearly 50 to 500 nm

The laser scanner showed more sensitivity in scanning the coated transparent objects. It was difficult to record any data of samples with 1, 2, and 3 layers of coating (less than 150 nanometres). The slide with 400 nanometre thickness (8 layers) was scanned but not with high quality. A new slide was coated up to 500 nanometres to improve the scanning result

(Figure 4-12). The slide was coated with approximately 10 layers. Increasing the coating thickness to almost 500 nanometres resulted in a good quality of laser scanning.

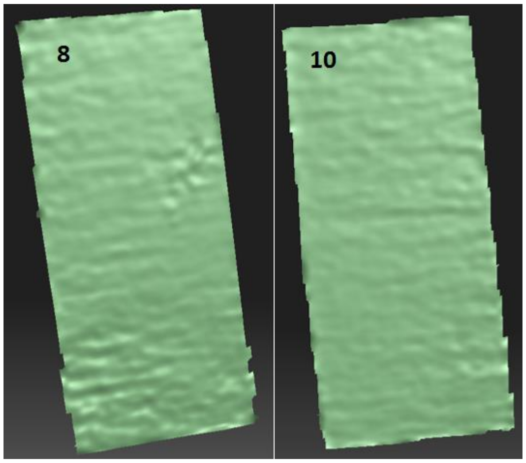

Figure 4-12: Laser scanning results for 8 and 10 layers of coating with 400 and 500 nm thickness

4.3.3 Structured-light Scanner Results for Reflective Samples

As mentioned before, optical scanners have difficulties in scanning reflective and shiny objects. Various mirror-polished gauge blocks were utilised to study the problems of shiny objects in this part of the experiments (Figure 4-13).

Figure 4-13: Gauge blocks as shiny samples with dark gray color

Another advantage of these blocks as target samples is that they have a dark grey colour on the side adjacent to the shiny face. Usually dark colours close to black cause difficulties in 3D scanning processes. Various blocks were covered with 1, 2, 4, 6, 8, and 10 layers of coating with approximate thickness of 50 to 500 nanometres (Figure 4-14).

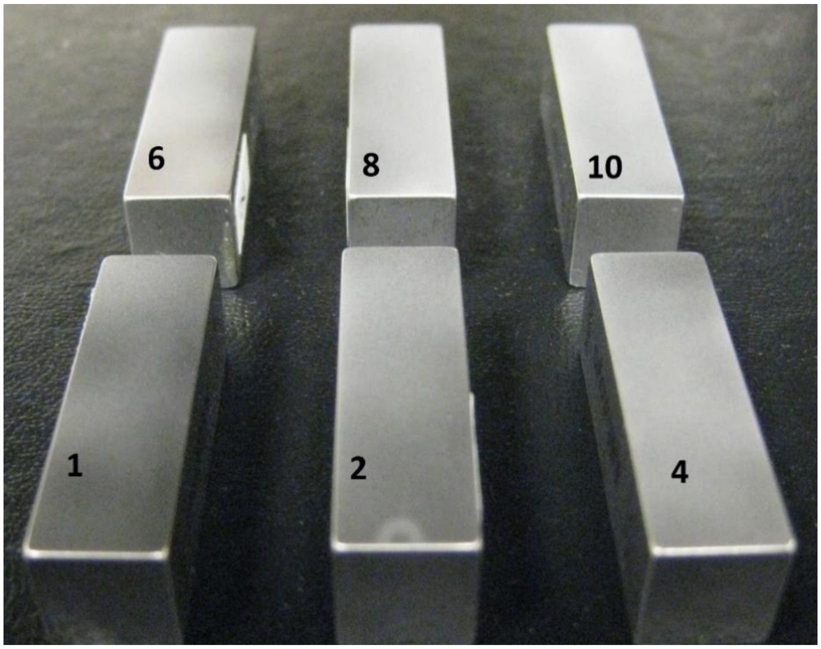

Figure 4-14: Coated blocks (digits show number of layers)

At first, all blocks were scanned by means of the structured-light scanner. Figure 4-15 shows that almost no data can be captured from the shiny surface of the uncoated block.

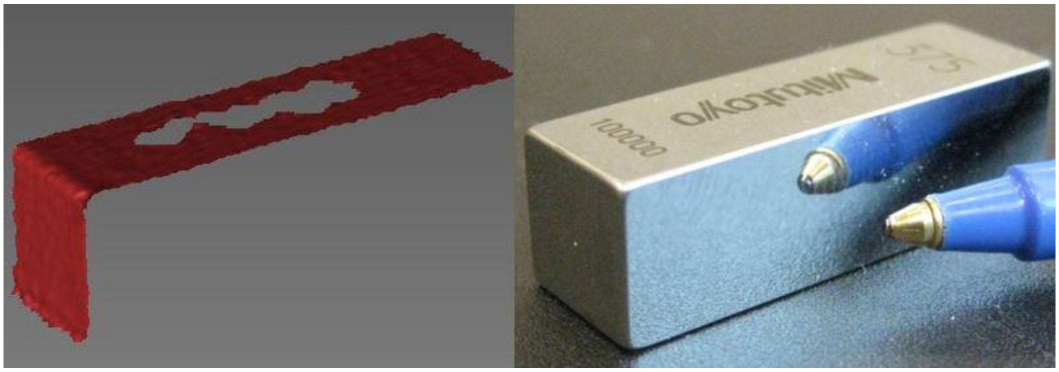

Figure 4-15: Scanning result of the uncoated block

Then all covered blocks were scanned and 8 to 10 layers of coating (400 to 500 nanometre thickness) improved the scanning result to a satisfactory amount for 3D modelling. Figure 4-16 shows the structured-light scanning results of the coated blocks.

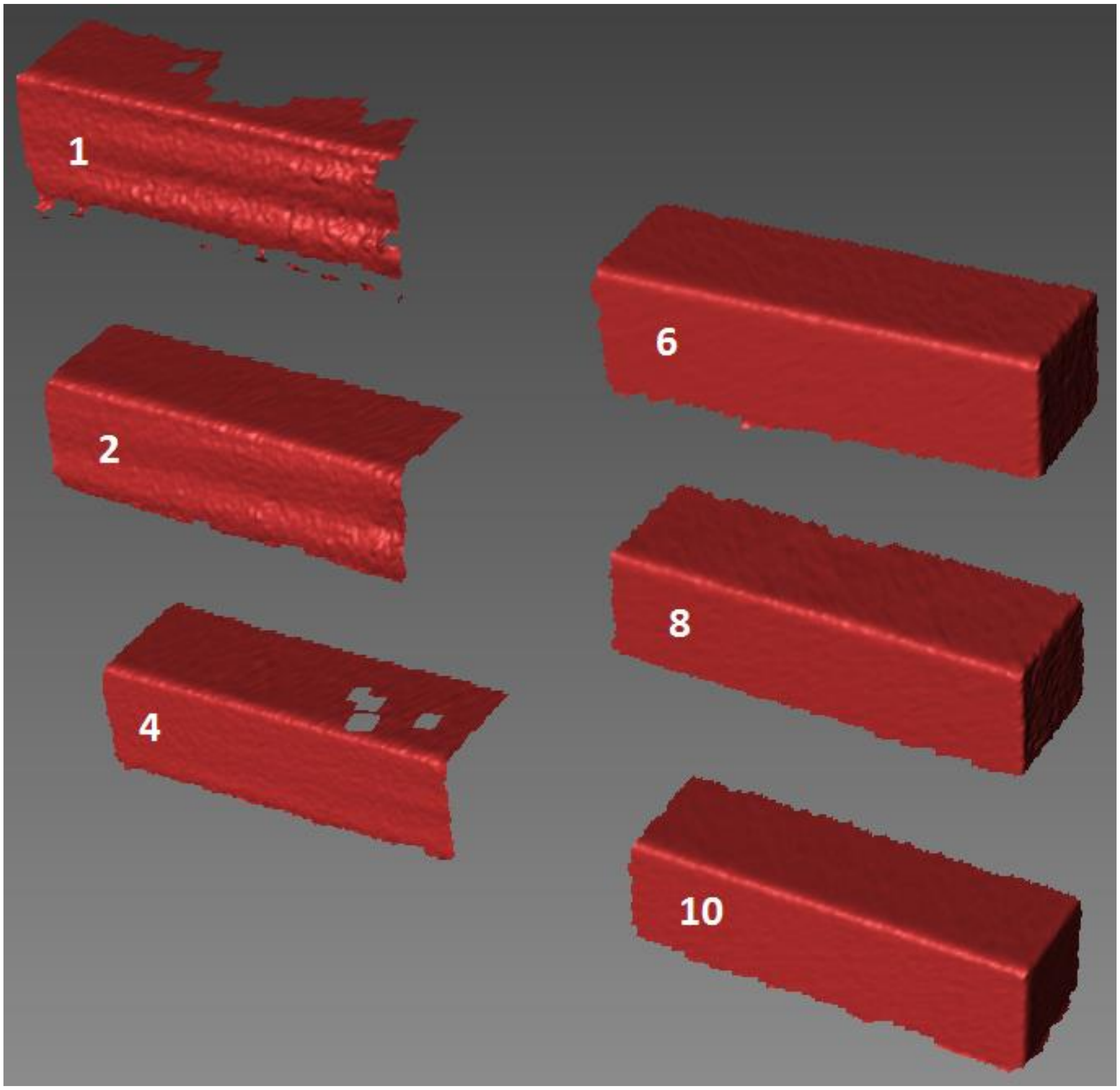

Figure 4-16: Scanning results of shiny blocks with the SLS

4.3.4 Laser Scanner Results for Reflective Samples

The same reflective blocks were scanned by means of the laser scanner. The scanning results showed that 0.5 micron thickness of coating can solve the problem of reflective objects in laser scanning, although it is difficult to scan blocks with coating thickness less than 200 nanometres. Figure 4-17 shows the laser scanning result of the coated blocks.

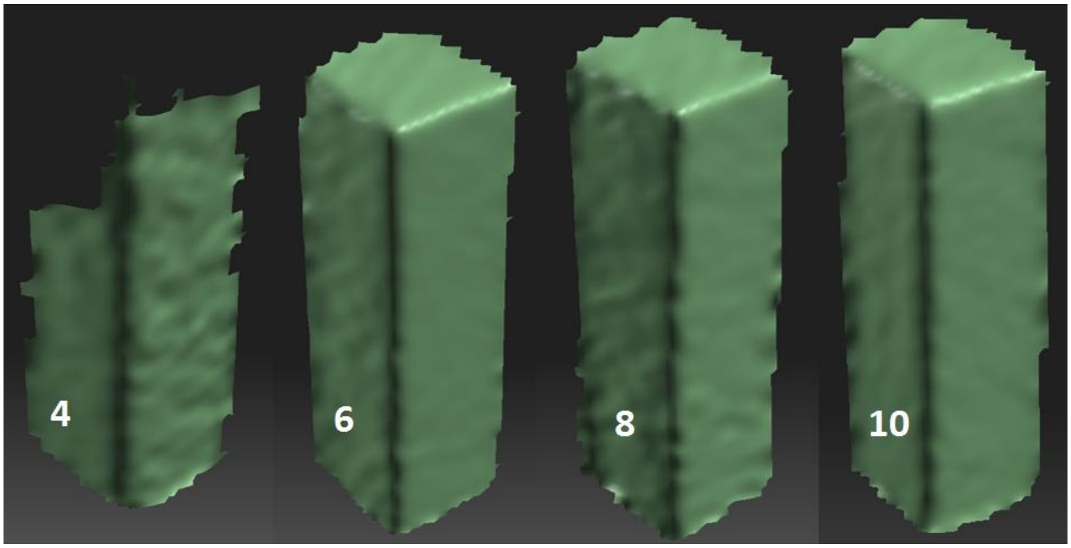

Figure 4-17: Laser scanning results of shiny blocks, where the digits show the number of coating layers

4.4. Scanning Results for Colour Samples

Surface colour can affect the scanning process of an object. Most industrial products have either shiny surfaces (due to machining process) or dark colour (due to their material). Dark colours limit the scanning result because of light absorption instead of reflection. Various colour samples with different colours were tested to study the influence of colour on 3D scanning.

Figure 4-18: Semi-gloss colour samples

The scanning result in Figure 4-19 shows that almost no data can be obtained from the black sample, and other dark colour samples such as navy blue and brown show noisy results. On the other hand, comparing the scanning quality and number of scanned points of all colour samples, white and grey colours show the best scanning results.

Figure 4-19: Scanning results for colour samples

The black sample then was coated with thickness of less than 300 nm and scanned. As can be seen in Figure 4-20 the scanning result of the black sample was improved significantly after coating.

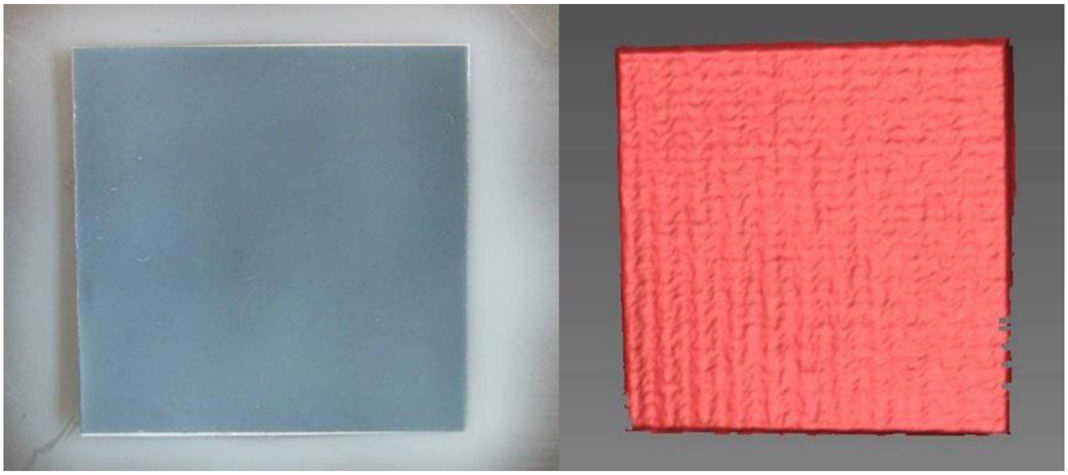

Figure 4-20: Coated black sample and its scanning result

4.5. Coating and Scanning of Grooves and Corners, a Comparison between Aerosol Spray and Atomization-based Spray

It has been noted that the newly designed spray system can disperse nano-sized particles over the surface and generate a thin and uniform layer of coating on the object. This ability can be noted more where coating is done over a groove or on a corner of an object. In aerosol spraying, apart from exiting a large amount of material from the nozzle, the spray discharges the pigments in a divergent manner which reduces control over the coating concentration and dispersion. In this situation the particles and the pigments can be agglomerated on a corner or inside a groove and it can cause an unwanted pile of pigments over the surface which affects the accuracy of part geometry measurement. To study this issue and for comparing the atomization-based spray system with an aerosol spray, a shiny aluminium part was selected. The part had been machined before and has two similar corners with 90 degree angle.

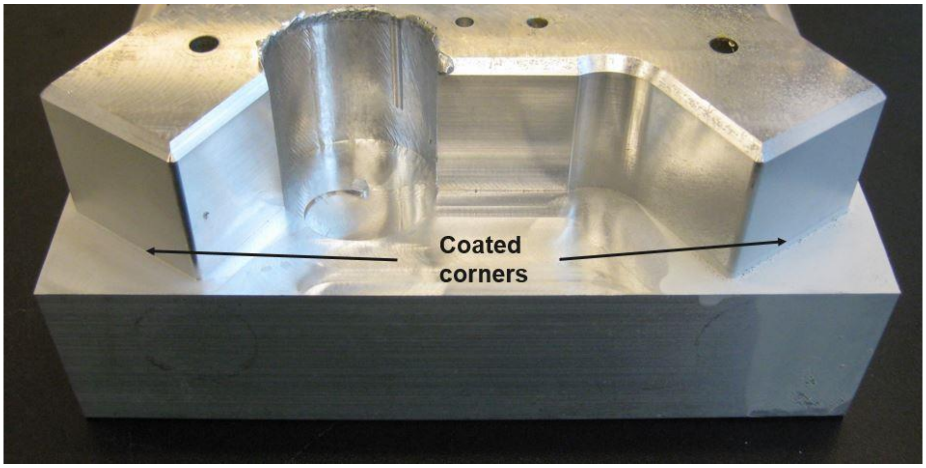

Figure 4-21: Reflective aluminium part to compare different spraying methods

Due to the reflective surface of the part, scanning was almost impossible without coating the object. Two corners of the part then were coated by the newly designed spray (Figure 4-21, left corner) and the aerosol spray (Figure 4-21, right corner) separately. Coating by means of the aerosol spray caused aggregation of pigments in the corner and affected detection of the smooth surface of the part in that area (Figure 4-22).

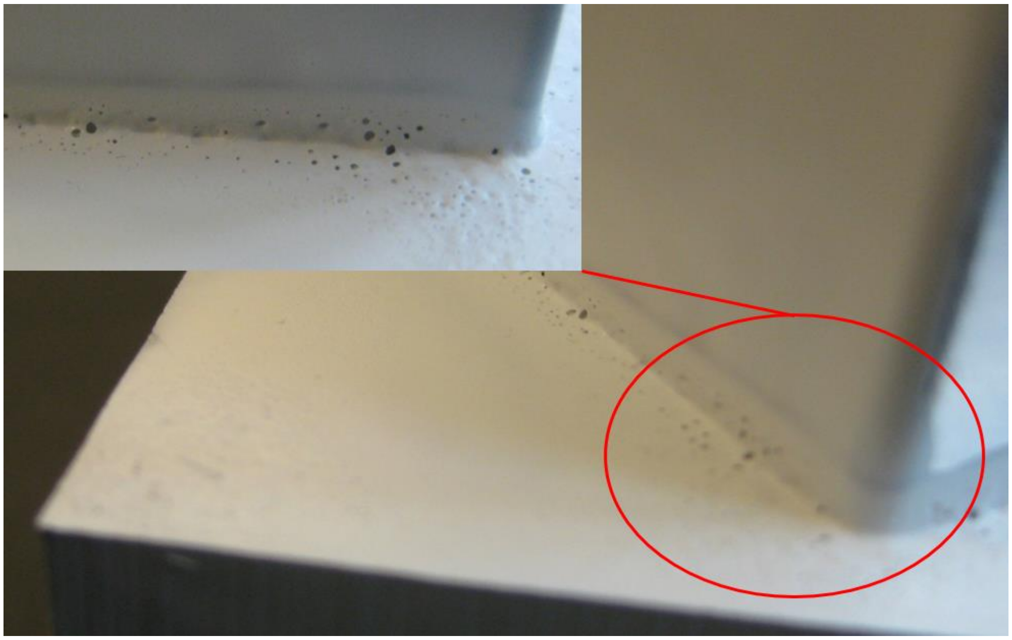

Figure 4-22: Corner coated by the aerosol spray

As can be seen in Figure 4-23, coating with the aerosol spray improved the scanning quality but it also caused a filleted corner on the model generated by the scanner.

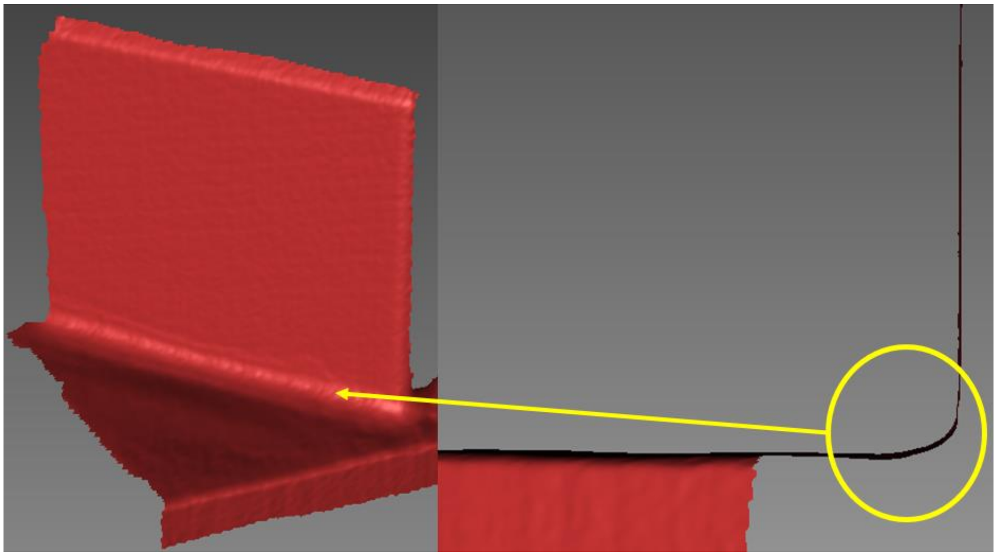

Figure 4-23: Aerosol spray effect on scanning result, side view on right

The mesh file was imported into Solidworks to measure the fillet generated in the corner. The result showed an approximate fillet with 2mm radius in the corner (Figure 4-24).

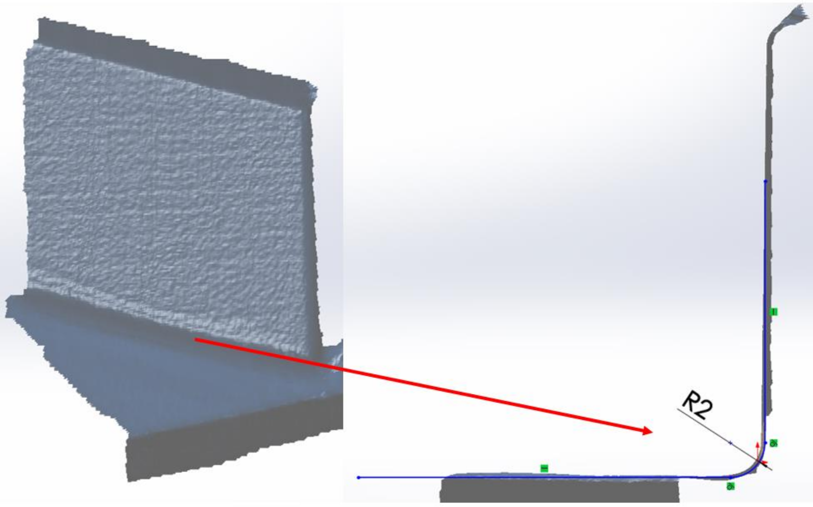

Figure 4-24: Imported mesh in Solidworks shows a 2mm fillet in the corner, side view on right

The other corner then was coated by the newly designed spray and scanned. Due to the shiny surface, the part was coated almost with 0.5 micron thickness to facilitate the scanning. The important issue was the uniform dispersion of the pigment over the surface. Also the coating did not cause a bulk of material in the corner. As can be seen in Figure 4-25, the right angle corner of the part did not get affected by the coating and the geometry did not change to a rounded part.

Figure 4-25: Coated corner by the atomization-based spray

The scanning result of the second corner shows a right angle similar to the actual part and a fillet shape is not built in the model (Figure 4-26).

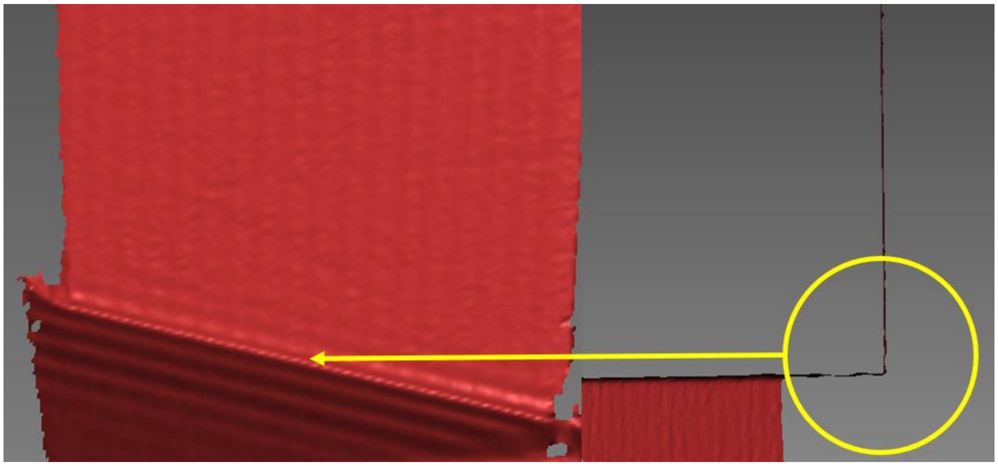

Figure 4-26: Effect of atomization-based spray on the scanning result, side view on right

Chapter 5 : Scanning of Actual 3D Parts and Comparison

3D scanning is widely in use in different industries for various applications. In some cases the surface characteristics of an object can impede the scanning process. As mentioned in previous chapters, covering the object surface temporarily with thin layers of coating facilitates the process and improves the scanning quality. However this is an acceptable solution only where the coating is permissible and does not affect the object in any manner.

One of the major applications of 3D scanning is in the manufacturing industry for reverse engineering and for inspection or quality control of manufactured parts. For inspection purposes, after scanning the manufactured part, the acquired 3D model is compared with the original 3D model for geometry control and inspection for any possible error during the production stage. Then in this case, if a part should be coated before scanning, the thickness of the applied coating plays an important role in the inspection process, as one wants to minimize any error due to coating. This error likely happens when coating is done with an aerosol spray due to the increase in thickness and the subsequent affects over the part geometry. As with atomization-based spray very thin layers of coating can be applied on the surface, and it possibly does not affect the part geometry. The thin layer of coating that is applied by the atomization-based spray can be easily removed from the surface after the scanning process. In this chapter, the efficiency of the atomization-based spray coating on 3D scanning is studied by using various parts with different applications.

5.1 Scanning Translucent and Shiny Cellphone Cases

3D scanners are widely used by electronics accessory companies which mainly produce cases for electronic devices such as smartphones and tablets. A case can be easily produced by having a precise 3D model of the device which can be acquired by a 3D scanner. Smartphones and tablets usually have highly reflective surfaces with black color which impedes the scanning process. Then in this case, applying a thin layer coating can facilitate 3D scanning while does not affect part geometry.

First, the rear cover of a smartphone that has a black and shiny surface was tested. Figure 5-1 shows that the scanning result of the uncoated part is quite noisy (left image) while applying a thin layer of coating (less than 0.2 microns) by means of the atomization-based spray sped up the scanning process and improved the 3D model quality.

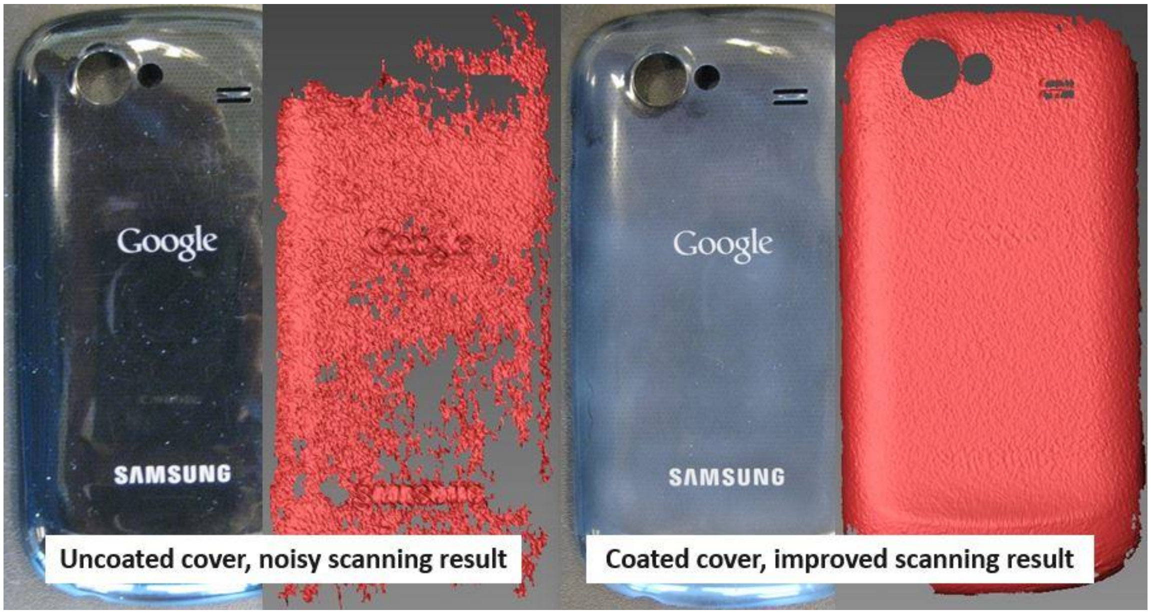

Figure 5-1: Scanning results of a black shiny cell case (uncoated left and coated right)

For the next trial a translucent cellphone case was selected and scanned. It was difficult to record its surface information and the scanned area shows a noisy result. In the case of a translucent part the reflection may happen from inside the object and cause subsurface scattering. The case was coated by means of the atomization-based spray with thickness of less than 0.5 microns and the result improved significantly as can be seen in Figure 5-2.

Figure 5-2: Scanning results of a translucent cell case (uncoated top and coated bottom)

A shiny turquoise cell phone case was scanned as the last example of cell covers. Comparing the scanning results before and after coating in Figure 5-3 shows that applying a thin layer of atomized pigments with thickness of less than 0.5 microns could improve the scanning result significantly to generate a proper 3D model of the sample.

Figure 5-3: Scanning results of a shiny cell case (uncoated top and coated bottom)

5.2 Scanning an Automotive Part, Gearbox Cam Shaft

After studying in Chapter 4 the effect of coating on corners on a shiny aluminium part, this issue was checked on an actual part. A gearbox cam shaft was scanned for a UVic formula SAE team. As can be seen in Figure 5-4, there are various grooves on the part which have almost a dark color. Optical scanners have some challenges on scanning dark objects as light cannot be reflected properly from the surface. In this sample, one single scan could not complete the 3D model generation of a specific area with a groove. The process had to be repeated from various angles. This can increase the scanning time and the number of scanned points which lead to a larger model in data size.

Applying a light coating on the same area enabled the complete 3D model generation with a single scan which improved the scanning time and quality of the entire object. The coating did not affect the part geometry as no pigment agglomeration occured in the corners.

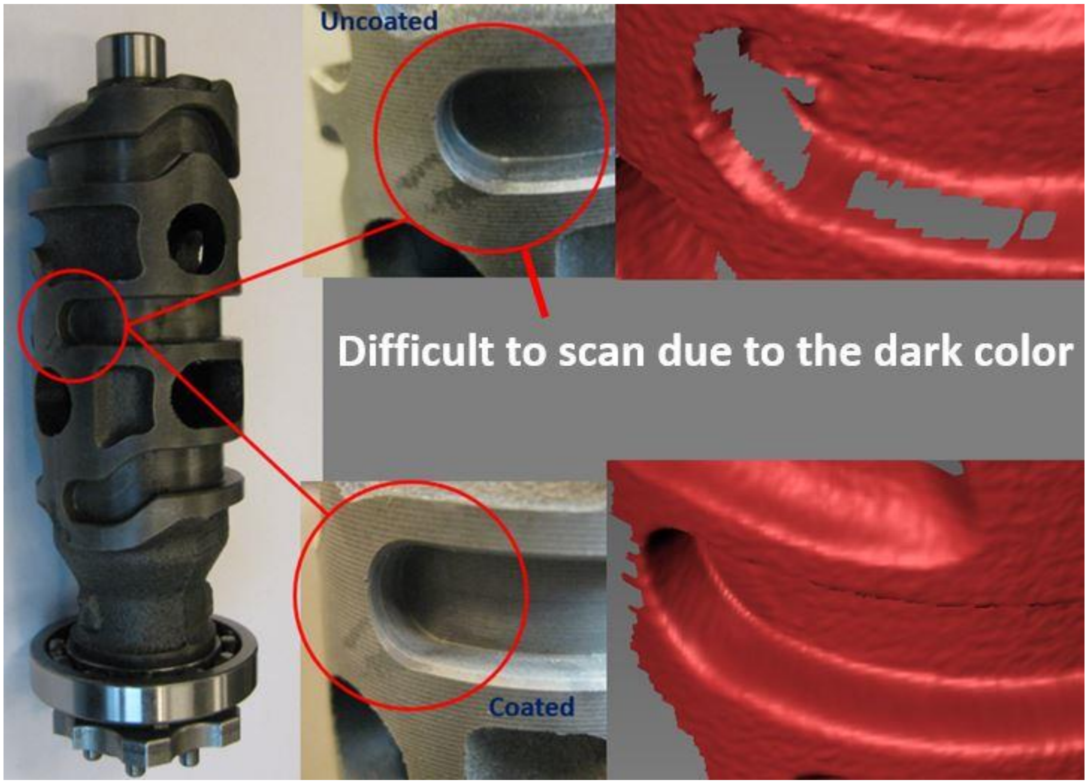

Figure 5-4: Coating inside the groove to ease the scanning process

The whole part was then scanned before and after coating. Although it was possible to scan the entire part without coating, it took around 40 minutes to complete the process as the scanning was done from various angles. Around 620,000 vertices were scanned for this sample before coating. The scanning process of the coated part took around 10 minutes and the result was more complete and smooth compared to the uncoated one. The number of scanned vertices were decreased to 455,000. Of course it should be kept in mind that it took more than 5 minutes to apply and remove the coating from the surface. The scanning results of the uncoated and coated cam shaft are shown in Figure 5-5.

Figure 5-5: Scanning results for uncoated part (left) with around 620,000 vertices in 40 minutes and coated part (right) with around 455,000 vertices in 10 minutes

5.3 Scanning a Shiny Motor Bike Clutch Lever

A shiny motor bike clutch lever is the last example studied to evaluate the efficiency of thin layer coating in the 3D scanning process. The lever is made out of anodized aluminium and has a reflective surface which impedes the scanning process. Figure 5-6 shows that the scanning result of the uncoated part is not appropriate for generating a complete 3D model and is noisy. Around 20,000 vertices were scanned for this model. After coating the lever with the help of an atomization-based spray with almost 0.3 micron thickness, the scanning result was improved drastically. The part was coated completely and almost 230,000 vertices were scanned for this model.

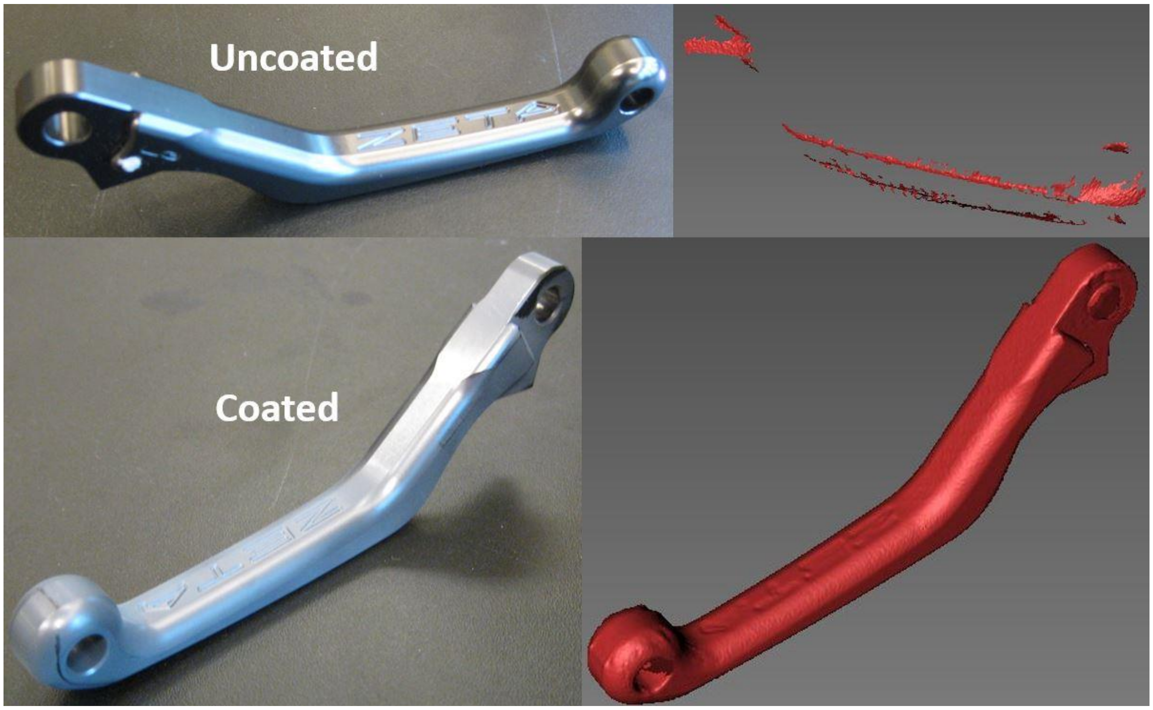

Figure 5-6: Scanning results of a shiny clutch lever (uncoated top and coated bottom)

Chapter 6 : Conclusions and Future Work

6.1 Conclusions

In this thesis a new spray coating system based on atomization of the coating solution was presented and its efficiency over improved optical 3D scanning applications was discussed. The new spray coating system consists of an atomizer to generate a mist of particles and a nozzle developed for proper dispersion of particles over the surface. Detailed features of the spray system were explained in Chapter 3.

In Chapter 2 an introduction to 3D scanning and its various techniques was offered. In studying the non-contact scanning technique it was mentioned that optical 3D scanners have difficulties in scanning some specific objects. Features such as transparency and reflectivity can impede the scanning process while optical 3D scanners are in use. In most cases, in industry, for improving the scanning quality the object would be sprayed by means of an aerosol spray with usually white opaque powder to change surface characteristics temporarily to matt and opaque. The applied coating should have three basic features:

- It should lead to diffuse reflection of light from the surface.
- It should be thin (less than 1 μm) to not affect object geometry and dimensions.
- It should be easily removable from the surface.

The conventional methods and devices of spray coating such as aerosol sprays are fast and effective but they coat the target objects with layers thicker than 10 microns. This may affect part geometry.

In this thesis the new coating system was used in various experiments to generate thin layer coating with less than 0.5 micron thickness and its efficiency in 3D scanning processes was studied.

In Chapter 4 titanium dioxide was introduced as the most suitable coating material for thin layer coating. Titanium dioxide pigments have high refractive index which increases hiding power with minimum possible thickness.

In Chapter 4, the atomization-based coating features were analyzed by means of a surface profilometer. The profilometer showed that each layer of coating generated for these experiments has 75 to 100 nm thickness. In this chapter microscope glass slides and gauge blocks were used as basic samples of fully transparent and fully reflective objects, respectively. These samples were selected to consider the worst cases in the scanning process. The experiments showed that thin layer coating up to 0.5 µm can improve the scanning results of basic samples for both structured light and laser scanners. Also it was mentioned that compared to the aerosol spray the new coating system can be efficiently used for objects in small dimensions and with small features.

Finally in Chapter 5, some actual objects from different industries were tested to evaluate the results. 3D scanning is used widely in manufacturing industry for different applications. Manufactured parts usually have reflective surfaces due to the machining process. 3D scanning is also used by electronics accessory companies which mainly produce cases for electronic devices such as smartphones and tablets. Smart phones and other electronic devices usually have black shiny surfaces. Such surfaces limit the scanning process. By using some actual parts from automotive and electronic industries, the performance of the new spray system was investigated for actual object scanning. The samples which were used in Chapter 5 showed that applying thin layers of coating by means of atomization-based spray coating can facilitate and accelerate the 3D scanning process of shiny and translucent parts and improve the results. The thin layer coating meets all three previously mentioned expectations.

6.2 Future Work

There is a lot of work that should be further conducted relating to the research in this thesis. Some future activities are listed below:

- Apart from the previously mentioned advantages, the designed coating system is quite slow compared to an aerosol spray. In general, the scanning process is quite fast and easy and the coating should be done as quickly and simply as scanning. In the case of large objects, the coating process with the atomization-based system can be time consuming.
- The coating system should be able to coat objects of small and large sizes properly. Different adaptors can be designed for the nozzle outlet for dispersion of pigments over smaller or larger areas.
- Titanium dioxide was introduced as a coating material for atomization-based spray coating; however its biosafety should be studied for this application. Titanium dioxide is used widely even in the food industry, but recently it has been classified by the International Agency for Research on Cancer (IARC) as an IARC Group 2B carcinogen “possibly carcinogenic to humans” especially if it appears as dust in human environment.

Bibliography

1. Remondino, F. and S. El-Hakim, *Image-based 3D Modelling: A Review.* The Photogrammetric Record, 2006. **21**(115): p. 269-291.
2. Curless, B., *Overview of active vision techniques.* SIGGRAPH 99 Course on 3D Photography, 1999.
3. Bernardini, F. and H. Rushmeier. *The 3D model acquisition pipeline*. in *Computer Graphics Forum*. 2002. Wiley Online Library.
4. Boehler, W., M.B. Vicent, and A. Marbs, *Investigating laser scanner accuracy.* The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 2003. **34**(Part 5): p. 696-701.
5. Trucco, E., R.B. Fisher, and A.W. Fitzgibbon, *Direct calibration and data consistency in 3-D laser scanning*. 1994: University of Edinburgh, Department of Artificial Intelligence.
6. Chen, T., et al. *Polarization and phase-shifting for 3D scanning of translucent objects*. in *Computer Vision and Pattern Recognition, 2007. CVPR'07. IEEE Conference on*. 2007. IEEE.
7. Yastikli, N., *Documentation of cultural heritage using digital photogrammetry and laser scanning.* Journal of Cultural Heritage, 2007. **8**(4): p. 423-427.
8. Sansoni, G., M. Trebeschi, and F. Docchio, *State-of-the-art and applications of 3D imaging sensors in industry, cultural heritage, medicine, and criminal investigation.* Sensors, 2009. **9**(1): p. 568-601.
9. Boehler, W., G. Heinz, and A. Marbs, *The potential of non-contact close range laser scanners for cultural heritage recording.* INTERNATIONAL ARCHIVES OF PHOTOGRAMMETRY REMOTE SENSING AND SPATIAL INFORMATION SCIENCES, 2002. **34**(5/C7): p. 430-436.
10. Remondino, F., *Heritage recording and 3D modeling with photogrammetry and 3D scanning.* Remote Sensing, 2011. **3**(6): p. 1104-1138.
11. Park, S.C. and M. Chang, *Reverse engineering with a structured light system.* Computers & Industrial Engineering, 2009. **57**(4): p. 1377-1384.
12. El-Hakim, S.F. *Three-dimensional modeling of complex environments*. in *Photonics West 2001-Electronic Imaging*. 2000. International Society for Optics and Photonics.
13. Shum, H. and S.B. Kang. *Review of image-based rendering techniques*. in *Visual Communications and Image Processing 2000*. 2000. International Society for Optics and Photonics.
14. Böhler, W. and A. Marbs. *3D scanning instruments*. in *Proceedings of the CIPA WG 6 International Workshop on Scanning for Cultural Heritage Recording, Ziti, Thessaloniki*. 2002.
15. Zexiao, X., W. Jianguo, and Z. Qiumei, *Complete 3D measurement in reverse engineering using a multi-probe system.* International Journal of Machine Tools and Manufacture, 2005. **45**(12): p. 1474-1486.
16. Chen, F., G.M. Brown, and M. Song, *Overview of three-dimensional shape measurement using optical methods.* Optical Engineering, 2000. **39**(1): p. 10-22.

17. Rocchini, C., et al. *A low cost 3D scanner based on structured light*. in *Computer Graphics Forum*. 2001. Wiley Online Library.
18. Beraldin, J.-A., et al., *Active 3D sensing.* 2003.
19. Geng, J., *Structured-light 3D surface imaging: a tutorial.* Advances in Optics and Photonics, 2011. **3**(2): p. 128-160.
20. Valkenburg, R.J. and A.M. McIvor, *Accurate 3D measurement using a structured light system.* Image and Vision Computing, 1998. **16**(2): p. 99-110.
21. Zhang, L., B. Curless, and S.M. Seitz. *Rapid shape acquisition using color structured light and multi-pass dynamic programming*. in *3D Data Processing Visualization and Transmission, 2002. Proceedings. First International Symposium on*. 2002. IEEE.
22. Boyer, K.L. and A.C. Kak, *Color-encoded structured light for rapid active ranging.* Pattern Analysis and Machine Intelligence, IEEE Transactions on, 1987(1): p. 14-28.
23. Pirodda, L., *Shadow and projection moiré techniques for absolute or relative mapping of surface shapes.* Optical Engineering, 1982. **21**(4): p. 214640-214640-.
24. Ryu, W.-J., et al., *A study on the 3-D measurement by using digital projection moiré method.* Optik-International Journal for Light and Electron Optics, 2008. **119**(10): p. 453-458.
25. Reid, G., R. Rixon, and H. Messer, *Absolute and comparative measurements of three-dimensional shape by phase measuring moiré topography.* Optics & Laser Technology, 1984. **16**(6): p. 315-319.
26. Choi, Y.-B. and S.-W. Kim, *Phase-shifting grating projection moiré topography.* Optical Engineering, 1998. **37**(3): p. 1005-1010.
27. Bartscher, M., et al., *Enhancement and proof of accuracy of industrial computed tomography (CT) measurements.* CIRP Annals-Manufacturing Technology, 2007. **56**(1): p. 495-498.
28. Davis, J. and P. Wells, *Computed tomography measurements on wood.* Industrial Metrology, 1992. **2**(3): p. 195-218.
29. Flisch, A., et al., *Industrial computed tomography in reverse engineering applications.* DGZ-fP-Proceedings BB, 1999.
30. Kruth, J.-P., et al., *Computed tomography for dimensional metrology.* CIRP Annals-Manufacturing Technology, 2011. **60**(2): p. 821-842.
31. Durá, E., J. Bell, and D. Lane. *Reconstruction of textured seafloors from side-scan sonar images*. in *Radar, Sonar and Navigation, IEE Proceedings-*. 2004. IET.
32. Slama, C.C., C. Theurer, and S.W. Henriksen, *Manual of photogrammetry*. 1980: American Society of photogrammetry.
33. Moffitt, F.H., *Photogrammetry.* 1959.
34. Hallert, B., *Photogrammetry, basic principles and general survey.* 1960.
35. Kraus, K., *Photogrammetry: geometry from images and laser scans*. 2007: Walter de Gruyter.
36. Baltsavias, E.P., *A comparison between photogrammetry and laser scanning.* ISPRS Journal of photogrammetry and Remote Sensing, 1999. **54**(2): p. 83-94.
37. Prados, E. and O. Faugeras, *Shape from shading*, in *Handbook of mathematical models in computer vision*. 2006, Springer. p. 375-388.

38. Zhang, R., et al., *Shape-from-shading: a survey*. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 1999. **21**(8): p. 690-706.
39. Moghaddam, B., et al. *Model-based 3D face capture with shape-from-silhouettes*. in *Analysis and Modeling of Faces and Gestures, 2003. AMFG 2003. IEEE International Workshop on*. 2003. IEEE.
40. Weik, S. *A passive full body scanner using shape from silhouettes*. in *Pattern Recognition, 2000. Proceedings. 15th International Conference on*. 2000. IEEE.
41. Boehler, W. and A. Marbs. *3D scanning and photogrammetry for heritage recording: a comparison*. in *Proceedings of the 12th International Conference on Geoinformatics*. 2004.
42. Levoy, M., et al. *The digital Michelangelo project: 3D scanning of large statues*. in *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*. 2000. ACM Press/Addison-Wesley Publishing Co.
43. Mongon, B. *What light color should a White-Light-Scanner use?* ; Available from: http://8-tree.com/wp-content/uploads/2012/11/CMSC-2012-What-light-color-should-a-White-Light-Scanner-use_v5-final.pdf.
44. ShapeGrabber. *Inspecting Transparent or Reflective Parts with a 3D Laser Scanner*. Available from: http://blog.shapegrabber.com/2012/05/.
45. Bi, Z. and S.Y. Lang, *A framework for CAD-and sensor-based robotic coating automation*. Industrial Informatics, IEEE Transactions on, 2007. **3**(1): p. 84-91.
46. Kuş, A., *Implementation of 3D optical scanning technology for automotive applications*. Sensors, 2009. **9**(3): p. 1967-1979.
47. Nasr, G.G., A.J. Yule, and L. Bendig, *Industrial sprays and atomization: design, analysis and applications*. 2002: Springer.
48. Lefebvre, A., *Atomization and sprays*. Vol. 1040. 1988: CRC press.
49. Erickson, J.J. and J.R. Marshall, *Ultrasonic spray coating system*. 1996, Google Patents.
50. Engle, R., *ADVANTAGES OF ULTRASONIC SPRAY COATINGS OF BIOMATERIALS ONTO DEVICES AND IMPLANTABLES*.
51. Gogate, P.R., R.K. Tayal, and A.B. Pandit, *Cavitation: A technology on the horizon*. Current Science, 2006. **91**(1): p. 35-46.
52. May, K., *The collison nebulizer: description, performance and application*. Journal of Aerosol Science, 1973. **4**(3): p. 235-243.
53. Jun, M.B., et al., *An experimental evaluation of an atomization-based cutting fluid application system for micromachining*. Journal of Manufacturing Science and Engineering, 2008. **130**(3).
54. Rukosuyev, M., C.S. Goo, and M.B. Jun, *Understanding the effects of the system parameters of an ultrasonic cutting fluid application system for micro-machining*. Journal of Manufacturing Processes, 2010. **12**(2): p. 92-98.