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3D Laser Scanners' Techniques Overview

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Abstract: ***A 3D scanner is a device that analyzes a real-world object or environment to collect data on its shape and possibly its appearance (i.e. color). The collected data can then be used to construct digital three-dimensional models. 3D laser scanning developed during the last half of the 20th century in an attempt to accurately recreate the surfaces of various objects and places. The technology is especially helpful in fields of research and design. The first 3D scanning technology was created in the 1960s. The early scanners used lights, cameras and projectors to perform this task. Many different technologies can be used to build these 3D scanning devices; each technology comes with its own limitations, advantages, and costs. Many limitations in the kind of objects that can be digitized are still present: for example, optical technologies encounter many difficulties with shiny, mirroring, or transparent objects. In this paper, techniques used in the 3D laser scanningwill be covered.***

Keywords: 3D; Laser; Scanner; Technique; Models.

1. Introduction

3D scanners are very analogous to cameras. Like cameras, they have a cone-like field of view, and like cameras, they can only collect information about surfaces that are not obscured. While a camera collects colour information about surfaces within its field of view, a 3D scanner collects distance information about surfaces within its field of view. The "picture" produced by a 3D scanner describes the distance to a surface at each point in the picture. This allows the three dimensional position of each point in the picture to be identified.

For most situations, a single scan will not produce a complete model of the subject. Multiple scans, even hundreds, from many different directions are usually required to obtain information about all sides of the subject. These scans have to be brought in a common reference system, a process that is usually called alignment or registration, and then merged to create a complete model. This whole process, going from the single range map to the whole model, is usually known as the 3D scanning pipeline [1].

The "picture" produced by a 3D scanner describes the distance to a surface at each point in the picture. This allows the three dimensional position of each point in the picture to be identified.

3D laser scanning developed during the last half of the 20th century in an attempt to accurately recreate the surfaces of various objects and places. The technology is especially helpful in fields of research and design. The first 3D scanning technology was created in the 1960s. The early scanners used lights, cameras and projectors to perform this task. Due to limitations of the equipment, it often took a lot of time and effort to scan objects accurately. After 1985, they were replaced with scanners that could use white light, lasers and shadowing to capture a given surface. Next is a brief history of the 3D scanning development [2].

2. 3D Laser Scanning History

With the advent of computers, it was possible to build up a highly complex model, but the problem came with creating that model.

So in the eighties, the toolmaking industry developed a contact probe. At least this enabled a precise model to be created, but it was so slow. The thinking was, if only someone could create a system, which captured the same amount of detail but at higher speed, it will make application more effective.

Therefore, experts started developing optical technology. Using light was much faster than a physical probe. This also allowed scanning of soft objects, which would be threatened by prodding. At that time, three types of optical technology were available:

- Point, which is similar to a physical probe in that it uses a single point of reference, repeated many times. This was the slowest approach as it involved lots of physical movement by the sensor.
- Area, which is technically difficult. This is demonstrated by the lack of robust area systems on sale.
- Stripe, the third system - was soon found to be faster than point probing as it used a band of many points to pass over the object at once, which was accurate too. Therefore, it matched the twin demands for speed and precision.

So stripe was clearly the way forwards, but it soon became apparent that the challenge was one of software. To capture an object in three dimensions, the sensor would make several scans from different positions. The challenge was to join those scans together, remove the duplicated data and sift out the surplus that inevitably gathers when you collect several million points of data at once.

One of the first applications was capturing humans for the animation industry. By the mid-nineties they had developed into a full body scanner. In 1994, 3D Scanners launched REPLICA - which allowed fast, highly accurate scanning of very detailed objects. Meanwhile Cyberware were developing their own high detail scanners, some of which were able to capture object colour too, but despite this progress, true three-dimensional scanning - with these degrees of speed and accuracy - remained elusive.

One company - Digibotics - did introduce a 4-axis machine, which could provide a fully 3D model from a single scan, but this was based on laser point - not laser stripe - and was thus slow. Neither did it have the six degrees of freedom necessary to cover the entire surface of an object, neither could it digitise colour surface.

While these optical scanners were expensive, Immersion and Faro Technologies introduced low-cost manually operated digitisers. These could indeed produce complete models, but they were slow, particularly when the model was detailed.
By this time, 3D modellers were united in their quest for a scanner, which was:

- accurate
- fast
- truly three dimensional
- capable of capturing colour surface, and
- realistically priced.

In 1996, 3D Scanners took the key technologies of a manually operated arm and a stripe 3D scanner - and combined them in ModelMaker. This incredibly fast and flexible system is the world's first Reality Capture System.It produces complex models and it textures those models with colour. Colour 3D models can now be produced in minutes.

3. 3D Laser Scanners Techniques

There are varieties of technologies for digitally acquiring the shape of a 3D object. A well-established classification [3] divides them into two types: contact and non-contact 3D scanners [4]. Non-contact 3D scanners can be further divided into two main categories, active scanners, and passive scanners. There are varieties of technologies that fall under each of these categories.

3.1 Contact Technique

3D contact scanners, generally calibrated to operate on a fixed platform, often contain a probe located at the end of an articulated mechanical arm. The arm may be robotically or manually manipulated over the part's surface. As the probe contacts the object's surface the scanner records the X,Y,Z position of the probe by taking positional measurements of the armature. The recorded positions form a point cloud, which can be used to calculate a 3D mesh. Some highly accurate 3D scanners called Coordinate Measuring Machines (CMMs) are often used by the manufacturing industry to inspect parts for early indications of assembly problems. 3D contact scanners suffer from slow scan rates and may not be ideal for delicate objects, such as precious artworks, as physical contact may damage or deform the surface [5].

3.1.1 Traditional coordination measuring machine (CMM)

Contact 3D scanners probe the subject through physical touch. A CMM (Coordinate Measuring Machine) is an example of a contact 3D scanner. A coordinate measuring machine (CMM) is a device for measuring the physical geometrical characteristics of an object. This machine may be manually controlled by an operator or it may be computer controlled. Measurements are defined by a probe attached to the third moving axis of this machine. Probes may be mechanical, optical, laser, or white light, amongst others. Figure (1) shows one of the CMM.

Figure 1: Coordinate Measuring Machine (CMM)

It is used mostly in manufacturing and can be very precise. The disadvantage of CMMs though, is that it requires contact with the object being scanned. Thus, the act of scanning the object might modify or damage it. This fact is very significant when scanning delicate or valuable objects such as historical artifacts. The other disadvantage of CMMs is that they are relatively slow compared to the other scanning methods. Physically moving the arm that the probe is mounted on can be very slow and the fastest CMMs can only operate on a few hundred hertz. In contrast, an optical system like a laser scanner can operate from 10 to 500 kHz.Other examples are the hand driven touch probes used to digitize clay models in computer animation industry.

The typical CMM is composed of three axes, an X, Y, and Z. These axes are orthogonal to each other in a typical three-dimensional coordinate system. Each axis has a scale system that indicates the location of that axis. The machine will read the input from the touch probe, as directed by the operator or programmer. The machine then uses the X,Y, Z coordinates of each of these points to determine size and position with micrometer precision typically.

Coordinate measuring machines include three main components [6]:

- The main structure which include three axes of motion
- Probing system
- Data collection and reduction system - typically includes a machine controller, desktop computer, and application software.

They are often used for:

- Dimensional measurement
- Profile measurement
- Angularity or orientation measurement
- Depth mapping
- Digitizing or imaging
- Shaft measurement

They are offered with features like:

- Crash protection
- Offline programming
- Reverse engineering
- Shop floor suitability
- SPC software and temperature compensation.
- CAD Model import capability
- Compliance with the DMIS standard
- I++ controller compatibility

The machines are available in a wide range of sizes and designs with a variety of different probe technologies. They can be operated manually or automatically through Direct Computer Control (DCC). They are offered in various configurations such as benchtop, freestanding, handheld, and portable.

3.1.1.1 Specific parts

3.1.1.1.1 Machine body

The first CMM was developed by the Ferranti Company of Scotland in the 1950s as the result of a direct need to measure precision components in their military products, although this machine only had 2 axes. The first 3-axis models began appearing in the 1960s (DEA of Italy) and computer control debuted in the early 1970s (Sheffield of the USA). Leitz Germany subsequently produced a fixed machine structure with moving table [7].

In modern machines, the gantry type superstructure has two legs and is often called a bridge. This moves freely along the granite table with one leg (often referred to as the inside leg) following a guide rail attached to one side of the granite table. The opposite leg (often outside leg) simply rests on the granite table following the vertical surface contour. Air bearings are the chosen method for ensuring friction free travel. In these, compressed air is forced through a series of very small holes in a flat bearing surface to provide a smooth but controlled air cushion on which the CMM can move in a frictionless manner. The movement of the bridge or gantry along the granite table forms one axis of the XY plane. The bridge of the gantry contains a carriage which traverses between the inside and outside legs and forms the other X or Y horizontal axis. The third axis of movement (Z axis) is provided by the addition of a vertical quill or spindle which moves up and down through the center of the carriage. The touch probe forms the sensing device on the end of the quill. The movement of the X, Y and Z-axes fully describes the measuring envelope. Optional rotary tables can be used to enhance the approachability of the measuring probe to complicated workpieces. The rotary table as a fourth drive axis does not enhance the measuring dimensions, which remain 3D, but it does provide a degree of flexibility. Some touch probes are themselves powered rotary devices with the probe tip able to swivel vertically through 90 degrees and through a full 360-degree rotation.

As well as the traditional three axis machines (as pictured above), CMMs are now also available in a variety of other forms. These include CMM arms that use angular measurements taken at the joints of the arm to calculate the position of the stylus tip. Such arm CMMs are often used where their portability is an advantage over traditional fixed bed CMMs. Because CMM arms imitate the flexibility of a human arm, they are also often able to reach the insides of complex parts that could not be probed using a standard three-axis machine.

3.1.1.1.2 Mechanical probe

In the early days of coordinate measurement mechanical probes were fitted into a special holder on the end of the quill. A very common probe was made by soldering a hard ball to the end of a shaft. This was ideal for measuring a whole range of flat, cylindrical or spherical surfaces. Other probes were ground to specific shapes, for example a quadrant, to enable measurement of special features. These probes were physically held against the workpiece with the position in space being read from a 3-Axis digital readout (DRO) or, in more advanced systems, being logged into a computer by means of a footswitch or similar device. Measurements taken by this contact method were often unreliable as machines were moved by hand and each machine operator applied different amounts of pressure on the probe or adopted differing techniques for the measurement.

A further development was the addition of motors for driving each axis. Operators no longer had to physically touch the machine but could drive each axis using a hand box with joysticks in much the same way as with modern remote controlled cars. Measurement accuracy and precision improved dramatically with the invention of the electronic touch trigger probe. The pioneer of this new probe device was David McMurtry who subsequently formed what is now Renishaw plc. Although still a contact device, the probe had a spring-loaded steel ball (later ruby ball) stylus. As the probe touched the surface of the component the stylus deflected and simultaneously sent the X, Y,Z coordinate information to the computer. Measurement errors caused by individual operators became fewer and the stage was set for the introduction of CNC operations and the coming of age of CMMs.

Optical probes are lens-CCD-systems, which are moved like the mechanical ones, and are aimed at the point of interest, instead of touching the material. The captured image of the surface will be enclosed in the borders of a measuring window, until the residue is adequate to contrast between black and white zones. The dividing curve can be calculated to a point, which is the wanted measuring point in space. The horizontal information on the CCD is 2D (XY) and the vertical position is the position of the complete probing system on the stand Z-drive (or other device component). This allows entire 3D probing.

3.1.1.1.3 New Probing Systems

There are newer models that have probes that drag along the surface of the part taking points at specified intervals, known as scanning probes. This method of CMM inspection is often more accurate than the conventional touch-probe method and most times faster as well.

The next generation of scanning, known as non-contact scanning includes high speed laser single point triangulation [8], laser line scanning [9], and white light scanning [Site 8], is advancing very quickly. This method uses either laser beams or white light that are projected against the surface of the part. Many thousands of points can then be taken and used to not only check size and position, but to create a 3D image of the part as well. This "point-cloud data" can then be transferred to CAD software to create a working 3D model of the part. These optical scanners often used on soft or delicate parts or to facilitate reverse engineering.

3.1.1.1.4 Micro Metrology Probes

Probing systems for microscale metrology applications are another emerging area [10][11]. There are several commercially available coordinate measuring machines (CMM) that have a microprobe integrated into the system, several specialty systems at government laboratories, and any number of university built metrology platforms for microscale metrology. Although these machines are good and in many cases excellent metrology platforms with nanometric scales their primary limitation is a reliable, robust, capable micro/nano probe. Challenges for microscale probing technologies include the need for a high aspect ratio probe giving the ability to access deep, narrow features with low contact forces so as to not damage the surface and high precision (nanometer level). Additionally microscale probes are susceptible to environmental conditions such as humidity and surface interactions such as stiction (caused by adhesion, meniscus, and/or Van der Waals forces among others).

Technologies to achieve microscale probing include scaled down version of classical CMM probes, optical probes, and a standing wave probe [12] among others. However, current optical technologies cannot be scaled small enough to measure deep, narrow feature, and optical resolution is limited by the wavelength of light. X-ray imaging provides a picture of the feature but no traceable metrology information.

3.1.1.2 Physical Principles

Optical probes and/or laser probes can be used (if possible in combination), which change CMMs to measuring microscopes or multi sensor measuring machines. Fringe projection systems, theodolite triangulation systems or laser distant and triangulation systems are not called measuring machines, but the measuring result is the same: a space point. Laser probes are used to detect the distance between the surface and the reference point on the end of the kinematic chain (i.e.: end of the Z-drive component). This can use an interferometric, focus variation, a light deflection or half beam shadowing principle.

3.1.2 Portable Coordinate Measuring Machines

Portable CMMs are different from "traditional CMMs" in that they most commonly take the form of an articulated arm. These arms have six or seven rotary axes with rotary encoders, instead of linear axes. Portable arms are lightweight (typically less than 20 pounds) and can be carried and used nearly anywhere. The inherent trade-offs of a portable CMM are manual operation (always requires a human to use it), and overall accuracy is somewhat to much less accurate than a bridge type CMM. Certain non-repetitive applications such as reverse engineering, rapid prototyping, and large-scale inspection of low-volume parts are ideally suited for portable CMMs.

3.1.3 Multi-Sensor Measuring Machines

Traditional CMM technology using touch probes is today often combined with other measurement technology. This includes laser, video or white light sensors to provide what is known as multi-sensor measurement [13].

3.2 Non-Contact Technique

Non-contact 3D scanners, as the name implies, do not make physical contact with an object surface. Instead, noncontact 3D scanners rely on some active or passive techniques to scan an object. The end result is a highly accurate cloud of points that can be used for reverse engineering, virtual assembly, engineering analysis, feature and surface inspection or rapid prototyping [5].

3.2.1 Non-Contact active techniques

Active scanners emit some kind of radiation or light and detect its reflection in order to probe an object or environment. Possible types of emissions used include light, ultrasound, or x-ray [4]. 3D Laser Scanning or 3D Laser Scanners can generally be categorized into three main categories; time of flight, phase shift, and laser triangulation. These laser-scanning techniques are typically used independently but can also be used in combination to create a more versatile scanning system. There are also numerous other laser scanning technologies that are hybrids and/or combinations of other 3D scanning technologies such as accordion fringe interferometry or conoscopic holography [14].

3.2.1.1 Time-of-flight

The time-of-flight 3D laser scanner is an active scanner that uses laser light to probe the subject. At the heart of this type of scanner is a time-of-flight laser rangefinder. The laser rangefinder finds the distance of a surface by timing the round-trip time of a pulse of light. A laser is used to emit a pulse of light and the amount of time before the reflected light is seen by a detector is timed. Since the speed of light c is known, the round-trip time determines the travel distance of the light, which is twice the distance between the scanner and the surface. If t is the round-trip time, then distance is equal to ($c.t/2$). The accuracy of a time-of-flight 3D laser scanner depends on how precisely we can measure the time (t):3.3 picoseconds (approx.) is the time taken for light to travel 1 millimeter.

The laser rangefinder only detects the distance of one point in its direction of view. Thus, the scanner scans its entire field of view one point at a time by changing the range finder's direction of view to scan different points. The view direction of the laser rangefinder can be changed either by rotating the range finder itself, or by using a system of rotating mirrors. The latter method is commonly used because mirrors are much lighter and can thus be rotated much faster and with greater accuracy. Typical time-of-flight 3D laser scanners can measure the distance of 10,000~100,000 points every second. Time-of-flight devices are also available in a 2D configuration. This is referred to as a Time-of-flight camera.

3.2.1.2 Phase Shift

Phase shift laser scanners work by comparing the phase shift in the reflected laser light to a standard phase, which is also captured for comparison. This is similar to time of flight detection except that the phase of the reflected laser light further refines the distance detection, similar to the vernier scale on a caliper.

In the phase shift method, the phase shift between the sent and the received signal with a certain wavelength is determined. The required distance can be then computed depending on the phase shift. The maximum rang which can be measured by a certain modulation is half of the modulation wavelength. Measuring with a high frequency modulation gives precise distances but smaller range. Ambiguity regarding the measured distance can be obtained because with increasing the distance above the maximum range the phase will vary periodically [15]. The ambiguity can easily be removed by measuring with two different modulation frequencies. Through frequency selective computation of the phase differences from both measurement channels, an unambiguous and precise range measurement can be obtained [16].

While the scanning speed of phase difference scanners is faster than the time of flight scanners, the point clouds resulted from scanners use the phase difference method is more noisy than those resulted from scanners use the time of flight method [17]. The measuring range of scanners employ the time-of-flight method (200-300m) is longer than the measuring range of scanners employ phase difference method (70-80m).

3.2.1.3 Triangulation

The triangulation 3D laser scanners are also active scanner that use laser light to probe the environment. With respect to time-of-flight 3D laser scanner, the triangulation laser shines a laser on the subject and exploits a camera to look for the location of the laser dot. Depending on how far away the laser strikes a surface, the laser dot appears at different places in the camera's field of view. This technique is called triangulation because the laser dot, the camera and the laser emitter form a triangle (see figure 2). The length of one side of the triangle, the distance between the camera and the laser emitter are known. The angle of the laser emitter corner is also known. The angle of the camera corner can be determined by looking at the location of the laser dot in the camera’s field of view. These three pieces of information fully determine the shape and size of the triangle and gives the location of the laser dot corner of the triangle. In most cases, a laser stripe instead of a single laser dot, is swept across the object to speed up the acquisition process. The National Research Council of Canada was among the first institutes to develop the triangulation based laser scanning technology in 1978 [18]. Figure (3) shows the generation of point cloud using triangulation with a laser stripe.

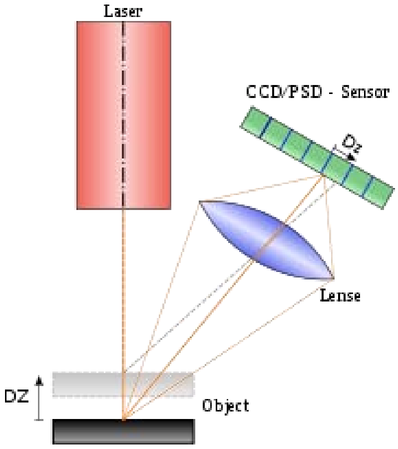

Figure 2: Principle of a laser triangulation sensor (Two object positions are shown)

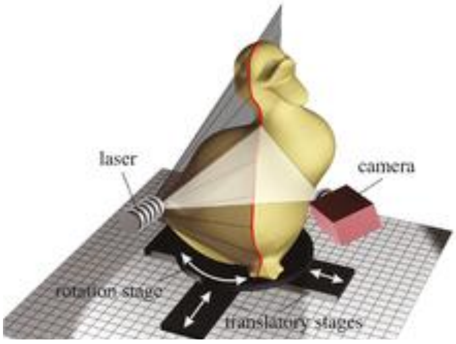

Figure 3: Point cloud generation using triangulation with a laser stripe

3.2.1.4 Strengths and Weaknesses

Time-of-flight and triangulation range finders each have strengths and weaknesses that make them suitable for different situations. The advantage of time-of-flight range finders is that they are capable of operating over very long distances, about kilometers [19]. These scanners are thus suitable for scanning large structures like buildings or geographic features. The disadvantage of time-of-flight range finders is their accuracy. Due to the high speed of light, timing the round-trip time is difficult and the accuracy of the distance measurement is relatively low, about millimeters. Triangulation range finders are exactly the opposite. They have a limited range of some meters, but their accuracy is relatively high. The accuracy of triangulation range finders is about tens of micrometers [20]. Time of flight scanners accuracy can be lost when the laser hits the edge of an object because the information that is sentback to the scanner is from two different locations for one laser pulse. The coordinate relative to the scanners position for a point that has hit the edge of an object will be calculated based on an average and therefore will put the point in the wrong place. When using a high resolution scan on an object the chances of the beam hitting an edge are increased and the resulting data will show noise just behind the edges of the object. Scanners with a smaller beam width will help to solve this problem but will be limited by range, as the beam width will increase over distance. Software can also help by determining that the first object to be hit by the laser beam should cancel out the second.

At a rate of 10,000 sample points per second, low resolution scans can take less than a second, but high resolution scans, requiring millions of samples, can take minutes for some time-of-flight scanners. The problem this creates is distortion from motion. Since each point is sampled at a different time, any motion in the subject or the scanner will distort the collected data. Thus, it is usually necessary to mount both the subject and the scanner on stable platforms and minimize vibration. Using these scanners to scan objects in motion is very difficult [21]. Recently, there has been research on compensating for distortion from small amounts of vibration [22].

When scanning in one position for any length of time slight movement can occur in the scanner position due to changes in temperature. If the scanner is set on a tripod and there is strong sunlight on one side of the scanner then that side of the tripod will expand and slowly distort the scan data from one side to another. Some laser scanners have level compensators built into them to counteract any movement of the scanner during the scan process.

3.2.2 Non-Contact active scanners

Common active non-contact 3D scanners include laser scanners, structured optical light scanners, Modulated light scanners, Computer Tomography scanners, Magnetic resonance imaging scanners, etc. Some of these scanners will be presented in the following sub-sections.

3.2.2.1 Conoscopic holography (Laser)

In a Conoscopic system, a laser beam is projected onto the surface and then the immediate reflection along the same ray-path are put through a conoscopic crystal and projected onto a CCD. The result is a diffraction pattern that can be frequency analyzed to determine the distance to the measured surface. The main advantage with Conoscopic Holography is that only a single ray-path is needed for measuring, thus giving an opportunity to measure for instance the depth of a finely drilled hole.

3.2.2.2 Structured light

Structured-light 3D scanners project a pattern of light on the subject and look at the deformation of the pattern on the subject. The pattern may be one-dimensional or two-dimensional. An example of a one-dimensional pattern is a line. The line is projected onto the subject using either an LCD projector or a sweeping laser. A camera, offset slightly from the pattern projector, looks at the shape of the line and uses a technique similar to triangulation to calculate the distance of every point on the line. In the case of a single-line pattern, the line is swept across the field of view to gather distance information one strip at a time.

An example of a two-dimensional pattern is a grid or a line stripe pattern. A camera is used to look at the deformation of the pattern, and an algorithm is used to calculate the distance at each point in the pattern. Consider an array of parallel vertical laser stripes sweeping horizontally across a target. In the simplest case, one could analyze an image and assume that the left-to-right sequence of stripes reflects the sequence of the lasers in the array, so that the leftmost image stripe is the first laser, the next one is the second laser, and so on. In non-trivial targets having holes, occlusions, and rapid depth changes, however, this sequencing breaks down as stripes are often hidden and may even appear to change order, resulting in laser stripe ambiguity. This problem can be solved using algorithms for multistripe laser triangulation. Structured-light scanning is still a very active area of research with many research papers published each year.

The advantage of structured-light 3D scanners is speed. Instead of scanning one point at a time, structured light scanners scan multiple points or the entire field of view at once. This reduces or eliminates the problem of distortion from motion. Some existing systems are capable of scanning moving objects in real-time.

A real-time scanner using digital fringe projection and phase-shifting technique (a various structured light method) was developed, to capture, reconstruct, and render high-density details of dynamically deformable objects (such as facial expressions) at 40 frames per second [23]. Recently, another scanner is developed. Different patterns can be applied to this system. The frame rate for capturing and data processing achieves 120 frames per second. It can also scan isolated surfaces, for example two moving hands [24].

3.2.2.3 Modulated light

Modulated light 3D scanners shine a continually changing light at the subject. Usually the light source simply cycles its amplitude in a sinusoidal pattern. A camera detects the reflected light and the amount the pattern is shifted by determines the distance the light traveled. Modulated light also allows the scanner to ignore light from sources other than a laser, so there is no interference.

3.2.3 Non-Contact passive technique

Passive non-contact 3D technique does not radiate the subject with energy. Instead, passive 3D scanners rely on reflected ambient radiation. Most scanners of this type detect visible light because it is readily available.

3.2.4 Non-Contact passive scanners

Passive scanners do not emit any kind of radiation themselves, but instead rely on detecting reflected ambient radiation. Most scanners of this type detect visible light because it is a readily available ambient radiation. Other types of radiation, such as infrared could also be used. Passive methods can be very cheap, because in most cases they do not need particular hardware but simple digital cameras. Common passive non-contact 3D scanners include stereoscopic video scanners, photometric scanners, Silhouette scanners and image-based modeling scanners. Examples of non-contact passive scanners will be presented in the following sub-sections.

3.2.4.1 Stereoscopic Systems

They usually employ two video cameras, slightly apart, looking at the same scene. By analyzing the slight differences between the images seen by each camera, it is possible to determine the distance at each point in the images. This method is based on the same principles driving human stereoscopic vision.

3.2.4.2 Photometric Systems

They usually use a single camera, but take multiple images under varying lighting conditions. These techniques attempt to invert the image formation model in order to recover the surface orientation at each pixel.

3.2.4.3 Silhouette Techniques

They use outlines created from a sequence of photographs around a three-dimensional object against a well contrasted background. These silhouettes are extruded and intersected to form the visual hull approximation of the object. With these approaches some concavities of an object (like the interior of a bowl) cannot be detected.

3.2.5 User assisted (Image-Based Modeling)

There are other methods that based on the user assisted detection and identification of some features and shapes on a set of different pictures of an object are able to build an approximation of the object itself. This kind of techniques is useful to build fast approximation of simple shaped objects like buildings. Various commercial packages are available like D-Sculptor, iModeller, Autodesk ImageModeler or PhotoModeler.

This sort of 3D scanning is based on the principles of photogrammetry. It is also somewhat similar in methodology to panoramic photography, except that the photos are taken of one object on a three-dimensional space in order to replicate it instead of taking a series of photos from one point in a three-dimensional space in order to replicate the surrounding environment.

3.3 Volumetric Techniques

3.3.1 Medical

Computed tomography (CT) is a medical imaging method, which generates a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images. Similarly Magnetic resonance imaging is another medical imaging technique that provides much greater contrast between the different soft tissues of the body than computed tomography (CT) does, making it especially useful in neurological (brain), musculoskeletal, cardiovascular, and oncological (cancer) imaging. These techniques produce a discrete 3D volumetric representation that can be directly visualized, manipulated, or converted to traditional 3D surface by mean of isosurface extraction algorithms [25].

3.3.2 Industrial

Although most common in medicine, Computed tomography, Microtomography and MRI are also used in other fields for acquiring a digital representation of an object and its interior, such as nondestructive materials testing, reverse engineering, or the study biological and paleontological specimens.

3.4 Model Reconstruction

3.4.1 From point clouds

The point clouds produced by 3D scanners can be used directly for measurement and visualization in the architecture and construction world.

Most applications, however, use instead polygonal 3D models, NURBS (Non-Uniform Rational B-Splines) surface models, or editable feature-based CAD models (aka Solid models).

- *Polygon mesh models*: In a polygonal representation of a shape, a curved surface is modeled as many small faceted flat surfaces (think of a sphere modeled as a disco ball). Polygon models—also called Mesh models, are useful for visualization, for some CAM (i.e., machining), but are generally "heavy" (i.e., very large data sets), and are relatively uneditable in this form. Reconstruction to polygonal model involves finding and connecting adjacent points with straight lines in order to create a continuous surface. Many applications, both free and non free, are available for this purpose (e.g. MeshLab, kubitPointCloud for AutoCAD, JRC 3D Reconstructor, imagemodel, PolyWorks, Rapidform, Geomagic, Imageware, Rhino etc.).
- *Surface models*: The next level of sophistication in modeling involves using a quilt of *curved* surface patches to model our shape. These might be NURBS, T Splines or other curved representations of curved topology. Using NURBS, our sphere is a true mathematical sphere. Some applications offer patch layout by hand but the best in class offer both automated patch layout and manual layout. These patches have the advantage of being lighter and more manipulable when exported to CAD. Surface models are somewhat editable, but only in a sculptural sense of pushing and pulling to deform the surface. This representation lends itself well to modeling organic and artistic shapes. Providers of surface modelers include Rapidform, Geomagic, Rhino, Maya, T Splines etc.
- *Solid CAD models*: From an engineering/manufacturing perspective, the ultimate representation of a digitized shape is the editable, parametric CAD model. After all, CAD is the common "language" of industry to describe, edit and maintain the shape of the enterprise's assets. In CAD, our sphere is described by parametric features which are easily edited by changing a value (e.g., center point and radius).

These CAD models describe not simply the envelope or shape of the object, but CAD models also embody the "design intent" (i.e., critical features and their relationship to other features). An example of design intent not evident in the shape alone might be a brake drum's lug bolts, which must be concentric with the hole in the center of the drum. This knowledge would drive the sequence and method of creating the CAD model; a designer with an awareness of this relationship would not design the lug bolts referenced to the outside diameter, but instead, to the center. A modeler creating a CAD model will want to include both Shape and design intent in the complete CAD model.

Vendors offer different approaches to getting to the parametric CAD model. Some export the NURBS surfaces and leave it to the CAD designer to complete the model in CAD (e.g., Geomagic, Imageware, Rhino). Others use the scan data to create an editable and verifiable feature based model that is imported into CAD with full feature tree intact, yielding a complete, native CAD model, capturing both shape and design intent (e.g. Geomagic, Rapidform). Still other CAD applications are robust enough to manipulate limited points or polygon models within the CAD environment (e.g., Catia).

3.4.2 From a set of 2D slices

CT, industrial CT, MRI, or Micro-CT scanners do not produce point clouds but a set of 2D slices (each termed a "tomogram") which are then 'stacked together' to produce a 3D representation. There are several ways to do this depending on the output required:

- Volume rendering: Different parts of an object usually have different threshold values or greyscale densities. From this, a 3-dimensional model can be constructed and displayed on screen. Multiple models can be constructed from various different thresholds, allowing different colors to represent each component of the object. Volume rendering is usually only used for visualisation of the scanned object.
- Image segmentation: Where different structures have similar threshold/greyscale values, it can become impossible to separate them simply by adjusting volume rendering parameters. The solution is called segmentation, a manual or automatic procedure that can remove the unwanted structures from the image. Image segmentation software usually allows export of the segmented structures in CAD or STL format for further manipulation.
- Image-based meshing: When using 3D image data for computational analysis (e.g. CFD and FEA), simply segmenting the data and meshing from CAD can become time consuming, and virtually intractable for the complex topologies typical of image data. The solution is called image-based meshing, an automated process of generating an accurate and realistic geometrical description of the scan data.

In figure (4), areas with the density of bone or air were made transparent, and the slices stacked up in an approximate free-space alignment. The outer ring of material around the brain are the soft tissues of skin and muscle on the outside of the skull.A black box encloses the slices to provide the black background. Since these are simply 2D images stacked up, when viewed on edge the slices disappear since they have effectively zero thickness. Each DICOM scan represents about 5mm of material averaged into a thin slice

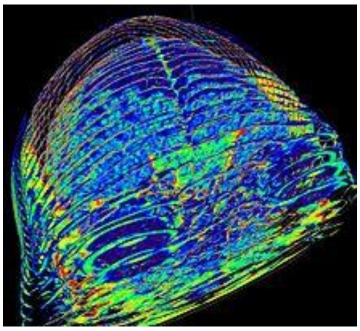

Figure 4: 3D reconstruction of the brain and eyeballs from CT scanned DICOM images

4. Conclusion

3D laser scanning equipment senses the shape of an object and collects data that defines the location of the object's outer surface. This distinct technology has found applications in many industries including discrete and process manufacturing, utilities, construction, archaeology, law enforcement, government, and entertainment.

Laser scanning technology has matured and developed in the past two decades to become a leading surveying technology for the acquisition of spatial information. Wide varieties of instruments with various capabilities are now commercially available. The high-quality data produced by laser scanners are now used in many of surveying's specialty fields, including topographic, environmental, and industrial. These data include raw, processed, and edited dense point clouds; digital terrain and surface models; 3D city models; railroad and power line models; and 3D documentation of cultural and historical landmarks.
3D laser scanners are working with three main types of techniques, which are:

- Time-of-Flight,
- Phase Shifting, and
- Trianglation

3D scanners are manily divided into three types, which are:

- Airborne scanners
- Teristerial scanners
- Hand-held scanners

Technology advances in the areas of data quality, software processing, and ease-of-use are rapidly expanding the applications for 3D laser scanning. The more effective product offerings are improving the business benefits of 3D laser scanning while achieving correspondingly greater revenue.

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