AN OVERVIEW OF 3D LASER SCANNING TECHNOLOGY

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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 useful for a wide variety of applications. These devices are used extensively by the entertainment industry in the production of movies and video games. Other common applications of this technology include industrial design, reverse engineering and prototyping, computer vision and documentation of cultural artifacts. Many different technologies can be used to build these 3D scanning devices. Each technology comes with its own limitations, advantages and costs. It should be remembered that many limitations in the kind of objects that can be digitized are still present as the optical technologies encounter many difficulties with shiny, mirroring or transparent objects.*

Key words: *3D scanner, ime-of-flight 3D laser scanner, color laser scanner, Optech's ILRIS-3D Intelligent Laser Ranging and Imaging System*

Introduction

1. Functionality

The purpose of a 3D scanner is usually to create a point cloud of geometric samples on the surface of the subject. These points (x,y,z) can then be used to extrapolate the shape of the subject and this process is called reconstruction. If color information is collected at each point, then the colors (R,G,B) on the surface of the subject can also be determined.

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 color information about surfaces within its field of view, 3D scanners collect 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. If a spherical coordinate system, is defined in which the scanner is the origin and the vector out from the front of the scanner is $\varphi=0$ and $\theta=0$, then each point in the picture is associated with a φ and θ. Together with distance, which corresponds to the r component, these spherical coordinates fully describe the three dimensional position of each point in the picture, in a local coordinate system relative to the scanner.

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.

There are however methods for scanning shiny objects, such as covering them with a thin layer of white powder that will help more light photons to reflect back to the scanner. Laser scanners can send trillions of light photons toward an object and only receive a small percentage of those photons back via the optics that they use. The reflectivity of an object is based upon the object's color or terrestrial albedo. A white surface will reflect lots of light and a black surface will reflect only a small amount of light. Transparent objects such as glass will only refract the light and give false three dimensional information.

2. Technology

The two types of 3D scanners are contact and non-contact. Non-contact 3D scanners can be further divided into two main categories, active scanners and passive scanners. There are a variety of technologies that fall under each of these categories.

2.1. Contact

Contact 3D scanners probe the subject through physical touch. A CMM (coordinate measuring machine) is an example of a contact 3D scanner. 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.

2.2. Non-Contact Active

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.

2.2.1. Time-of-flight

This **lidar** scanner may be used to scan buildings, rock formations, etc., to produce a 3D model. The lidar can aim its laser beam in a wide range: its head rotates horizontally, a mirror flips vertically. The laser beam is used to measure the distance to the first object on its path.

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 range finder. The laser range finder 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 a 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 . Clearly the accuracy of a time-of-flight 3D laser scanner depends on how precisely we can measure the t time: 3.3 picoseconds (approx.) is the time taken for light to travel 1 millimetre.

The laser range finder 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 range finder can be changed by either 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.

2.2.2. Triangulation

Principle of a laser triangulation sensor. Two object positions are shown fig.1. The triangulation 3D laser scanner is also an active scanner that uses 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 exploit 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. The length of one side of the triangle, the distance between the camera and the laser emitter is 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.

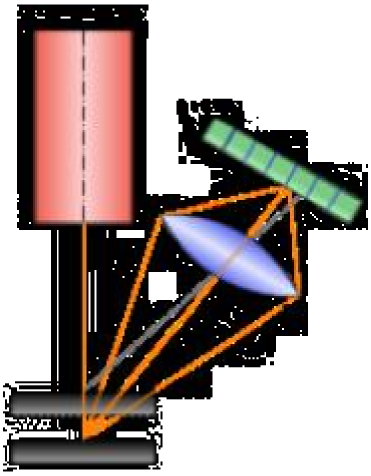

Figure 1. Principle of a laser triangulation sensor.
Two object positions are shown

Notes on Time-of-flight and Triangulation Scanners

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, on the order of kilometers. 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, on the order of 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 on the order of tens of micrometers.

With time of flight scanners accuracy can be lost when the laser hits the edge of an object because the information that is sent back to the scanner is from two different locations for one laser pulse. The co-ordinate 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.

Recently, there has been research on compensating for distortion from small amounts of vibration. 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 compensator built into them to counteract any movement of the scanner during the scan process.

2.2.3. Conoscopic Holography

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.

2.2.4. 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 a fairly complex algorithm is used to calculate the distance at each point in the pattern. One reason for the complexity is ambiguity. 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 particular problem was recently solved by a breakthrough technology called Multistripe Laser Triangulation (MLT). 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.

2.2.5. 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.

2.3. Non-Contact Passive

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.

2.3.1. Stereoscopic

Stereoscopic systems 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 human stereoscopic vision.

2.3.2. Silhouette

These types of 3D scanners 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 kinds of techniques some kind of concavities of an object (like the interior of a bowl) are not detected.

2.3.3. User Assisted (i.e. 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 are useful to build fast approximation of simple shaped objects like buildings. Various commercial packages are available like iModeller, D-Sculptor or RealViz-ImageModeler.

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. Reconstruction

The point clouds produced by 3D scanners are usually not used directly. Most applications do not use point clouds, but instead use polygonal 3D models. The process of converting a point cloud into a polygonal 3D model is called **reconstruction**. Reconstruction involves finding and connecting adjacent points in order to create a continuous surface. Many algorithms are available for this purpose (eg. photomodeler, imagemodel). These algorithms are designed largely based on the mathematics of the radon transform, statistical knowledge of the data acquisition process and geometry of the data imaging system. In medical tomography, the filtered back projection algorithm and its variants are the most efficient algorithms currently in use.

4. Technology - Color Laser Scanner

Developed over a 17 year period at the National Research Council of Canada (NRC), the Arius3D 3D color imaging system consists of a laser scanner and a motion control system for moving the camera. Scanned data is recorded and processed by software to transform the data into high-quality, 3D color images irrespective of ambient light. The system employs the principles of high resolution laser triangulation and synchronous scanning to produce high-fidelity digital representations of real-world objects at unprecedented resolution. The laser scanning mechanism characterizes each point on the scanned object according to its color and location in 3-space. It does this by scanning the surface of an object with three different laser wavelengths (red, green and blue) in one focused beam, and recording the reflected light. The X co-ordinate of each point on the object is calculated from an accurate measurement of the position of the scanning mirror in the camera. The Y co-ordinate is calculated from an accurate measurement of the camera's motion system. The Z, or range co-ordinate, is calculated through laser triangulation within the camera.

At the same time, the color information at each point is gathered by measuring the intensity of the three returning laser beams. Color intensity measurements are an accurate measurement of the surface color of the scanned object. Each point on the object is described by 6 numeric values; positional values X, Y, and Z, and surface color values R, G, and B.

5. Applications of 3D Laser Scanning

5.1. Material Processing and Production

Laser scanning describes a method where a surface is sampled or scanned using laser technology. Several areas of application exist that mainly differ in the power of the lasers that are used, and in the results of the scanning process. Lasers with low power are used when the scanned surface doesn't have to be influenced, e.g. when it has to be digitized. Confocal or 3D laser scanning are methods to get information about the scanned surface. Depending on the power of the laser, its influence on a working piece differs: lower power values are used for laser engraving, where material is partially removed by the laser. With higher powers the material becomes fluid and laser welding can be realized, or if the power is high enough to remove the material completely, then laser cutting can be performed. Also for rapid prototyping a laser scanning procedure is used when for example a prototype is generated by laser sintering.

The principle that is used for all these applications is the same: software that runs on a PC or an embedded system and that controls the complete process is connected with a scanner card. That card converts the received vector data to movement information which is sent to the scanhead. This scanhead consists of two mirrors that are able to deflect the laser beam in one level (X- and Y-coordinate). The third dimension is - if necessary - realized by a specific optic that is able to move the laser's focal point in the depth-direction (Z-axis).

The third dimension is needed for some special applications like the rapid prototyping where an object is built up layer by layer or for in-glass-marking where the laser has to influence the material at specific positions within it. For these cases it is important that the laser has as small a focal point as possible.

For enhanced laser scanning applications and/or high material throughput during production, scanning systems with more than one scanhead are used. Here the software has to control what is done exactly within such a multihead application: it is possible that all available heads have to mark the same to finish processing faster or that the heads mark one single job in parallel where every scanhead performs a part of the job in case of large working areas.

5.2. Construction Industry and Civil Engineering

- As-built drawings of Bridges, Industrial Plants, and Monuments
- Documentation of historical sites
- Site modeling and lay outing
- Quality control
- Quantity Surveys
- Freeway Redesign
- Establishing a bench mark of pre-existing shape/state in order to detect structural changes resulting from exposure to extreme loadings such as earthquake, vessel/truck impact or fire.
- Create GIS (Geographic information system) maps

5.3. Entertainment

3D scanners are used by the entertainment industry to create digital 3D models for both movies and video games. In cases where a real-world equivalent of a model exists, it is much faster to scan the real-world object than to manually create a model using 3D modeling software. Frequently, artists sculpt physical models of what they want and scan them into digital form rather than directly creating digital models on a computer.

5.4. Reverse Engineering

Reverse engineering of a mechanical component requires a precise digital model of the objects to be reproduced. Rather than a set of points a precise digital model is typically represented by a set of surfaces such as a set of flat triangular surfaces, a set of flat or curved NURBS surfaces, or ideally for mechanical components a CAD solid which is composed of a CAD subset of NURBS surfaces. A 3D scanner can be used to digitize free-form or gradually changing shaped components as well as prismatic geometries whereas a coordinate measuring machine is usually used only to determine simple dimensions of a highly prismatic model. These data points are then processed to create a usable digital model.

5.5. Cultural Heritage – Our Team's Practical Work

There have been many research projects undertaking the scanning of historical sites and artifacts. Part of the work of the 2nd series of INTERREG IIID seminars and conference was to engage in a practical exercise of 3D scanning of a historical site in Bulgaria. We organised the project, the chosen site was the Assen fortress in Assenovgrad. The fortress was built to guard a mountain pass from invaders it sits on a high peak overlooking the passage, what remains of it today is the church. The work was planned to last 4 days (excluding travel time) during April 2008, scanning the fortress from various angles to get a complete as possible scan of the whole fortress, and then analysing the results for accuracy/reliability. Unfortunately due to bad weather (rain/snow) the team had only 2 days to complete the scans of the fortress.

5.5.1. Scanning. For the scanning of the fortress is used **Optech's ILRIS-3D Intelligent Laser Ranging and Imaging System,** which is a complete, fully portable, laser-based imaging and digitizing system. A compact and highly integrated package with digital image capture and sophisticated software tools, ILRIS-3D is field-ready and requires no specialized training for deployment. About the size of a motorized total station, with an on-board high resolution digital camera and large-format LCD viewfinder, ILRIS-3D has a visual interface similar to that of a digital camera.

Field deployment is made extremely efficient by ILRIS-3D's high data rate and large dynamic range - from 3 m to >1,500 m. ILRIS-3D is deployed by a single operator. The modular design ensures that all functionality is available, making operation as easy as possible. Setup is rapid and simple - no leveling required - and the system is controlled via a wireless handheld PDA or laptop. The target area and scan status are displayed locally on screen, and data is written directly to removable media. Measurement area and spot density are user definable.

It is rated for operation from 0^{o}C to 40^{o}C, and is weatherproof for use outdoors. The system's Class 1 and Class 1M eyesafety rating, large dynamic collection range and compact size all ensure that difficult surveys can be completed quickly, safely and accurately.

5.5.2. Data Processing. The data processing of the scans of Assen's fortress was done with Pointstream 3DImageSuite. Pointstream 3D ImageSuite for Windows.

3DImageSuite is a specialized application for processing point cloud data captured using three dimensional imaging systems. 3DImageSuite contains an advanced set of tools that will allow you to view and edit point cloud data in xyzrgb format.

View and analyze 3D data

- View point cloud data as fully surfaced 3D models
- View 3D models in stereo display mode
- Manipulate lighting parameters and position
- Create cross section cuts through cloud data
- Create rapid prototype models from point cloud data

Process point cloud data

- Clean, edit, and filter individual component images
- Align and merged multiple component images
- Create, modify, and analyze color of point cloud data

Author presentation content

- Sample and compress 3D images
- Create high quality 2D images for display or print
- Create animated image sequences
- Embed 3D images in Microsoft Desktop Applications

Conclusions

3D laser scanning is a highly adaptable and versitle technological tool which offers solutions to problems encountered in many spheres of scientific and cultural study.

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