3D RECONSTRUCTION METHODS, A SURVEY

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Abstract: 3D reconstruction technologies have evolved over the years. In this paper we try to highlight the evolution of the scanning technologies. The idea of a survey came up with our decision to look at 3D reconstruction methods. Little has been written about the methods in general, yet many developments have taken place in this area. This survey will prove useful for those intending to embark on research in 3D reconstruction technologies or are considering acquiring a 3D scanner. The survey takes a look at the major reconstruction methods, which are; Laser triangulation, Stereoscopy, Conoscopic holography and Moiré Interferometry. A review of the major producers of scanning technology for 3D reconstruction is also carried out.

1 INTRODUCTION

3D reconstruction methods are classified into passive and active. Passive methods do not involve interaction with the object, whereas active methods use contact or a projection of some form of energy onto the object. Our main in this paper is given to the active methods that use the projection of a form of energy onto the objects, light in our case. Active methods involving contact with the object are being phased out due to their slow reconstruction process and the need for less contact with the object to avoid them getting damaged (Curless, B). In this paper, our main focus will be on the optical non contact methods that offer faster reconstructions since they are commonly applied in the manufacturing industry. In the field, the main method used to realise reconstructions is optical laser triangulation.

Section two deals with the various methods of 3D reconstruction, whereas section 3 analyses the 3D scanners on the market. We make comparisons based on the technical specifications provided by the manufacturers. The last section contains a summary of all the results from the survey. Given the importance of faster prototyping in modern industry, one can easily appreciate the amount of time and money that is saved when 3D scanning methods are used. At present many of the leading manufacturing industries have incorporated in their production lines systems for 3D scanning. This has helped increase their productivity and save on the time it takes for a product to be released on the market. On the whole, the benefit of these scanning systems is the improved product quality, time to market and the reduction of the overall production cost.

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2 3D RECONSTRUCTION METHODS

As has been mentioned in the previous section, here we take a look at the broad range of 3D reconstruction methods.

2.1 Laser triangulation

Laser triangulation is the most common method used in commercial 3D scanners. The principle of operation of Laser triangulation involves the projection of a ray of light over an object in the form of a point. If the object is to be captured by a camera, only a bright spot should be detected. Therefore knowing with precision the relative angle of projection with respect to the base line, it is possible to determine the position of the point in space. The variants of laser triangulation are based on the many ways of projecting and detecting the light rays. In the case of a point source, the whole scene has to be scanned both vertically and horizontally to obtain the depth. If instead of projecting a point, a line is projected, the depth of all the points on the line can be obtained at the same time. This explains why techniques based on the projection of a line are much faster than the projection of a single point. One may use various methods to project the light onto the scene, each one with its merits and demerits. The precision, the presence of blind spots, where triangulation is made impossible, and the speed of scanning the scene are the principle factors to be taken into account when choosing the kind of technique.

Principle of operation

Consider the figure shown below. A ray of light originating from a laser diode is focussed on an object at point P. The ray is observed using a camera placed at an angle to the object. The separation of the camera from the laser diode is known. Using triangulation theory the distance of the object in the z axis is recorded.

The laser diode is located on the x-axis, at a known distance from the camera b. Assuming P is in the x,z plane, the distance and projection angle of the laser diode are established before hand.

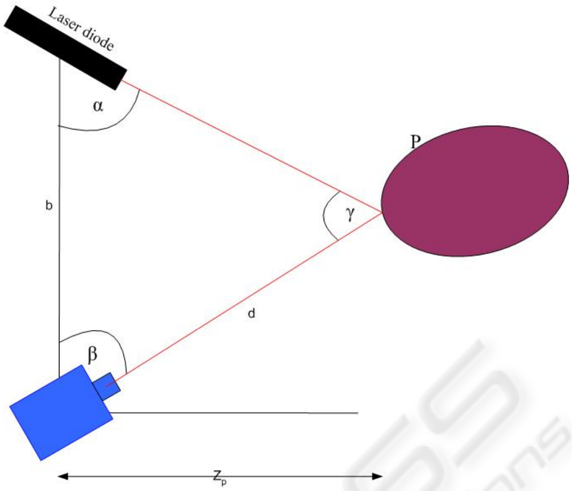

Figure 1: Triangulation setup.

Our next main problem is to solve for the distance Z_p from the object. Using similar triangles, the sine rule is applied to the setup. A derivation of the distance Zp is obtained can be found in the reference (Klaus D.)

2.2 Stereoscopy

Stereo vision refers to the ability to deduce information on the 3D structure and distance of a scene from two or more images of taken from different viewpoints. The name stereoscopy was given to this method by Sir Charles Wheatstone (Wheatstone, C). Stereo vision involves two processes: the binocular fusion observed by the two eyes, and the reconstruction of the three-dimensional image. The pre-image of the matching points can be found at the intersection of the rays passing through these points and the associated pupil centres or pinholes. In a stereo system, we look for correspondences existent between the two images i.e. which parts in both images are projections of the same scene. Having obtained the correspondences, the 3D structure is determined using epipolar geometry. By estimating the disparity between two images, the height of each point is evaluated. The robustness of the process is ensured by modeling and taking into account the geometric nature of the elements observed.

Principle of Stereoscopy

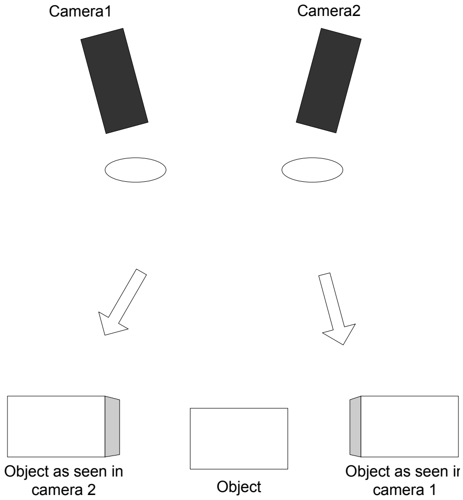

Figure 2: Stereo setup.

As was mentioned above, stereo vision involves the matching of points observed in two images captured by two cameras. This matching is done using epipolar geometry. Epipolar geometry involves the the observation of a single point in two images and relating the coordinates in each of the images. (Owen, R)

2.3 Holography

Holography is a technique by which a wave front can be recorded and subsequently reconstructed in the absence of the original wave front. The method was proposed and demonstrated by Gabor in 1948 long before the laser came into existence. Observation of this reconstructed wave front gives exactly the same physical effect as the observation of the original wave front. On illuminating the scene after removing the object, a three dimensional image is observed as though the object was still present. Leith and Upatnieks were the pioneers in applying holography to three dimensional imagery way back in 1964. This depended largely on the availability of the HeNe laser, which had an excellent temporal and spatial coherence (Goodman, C).

Figure 3 shows the geometry used for recording holograms of a three dimensional scene.

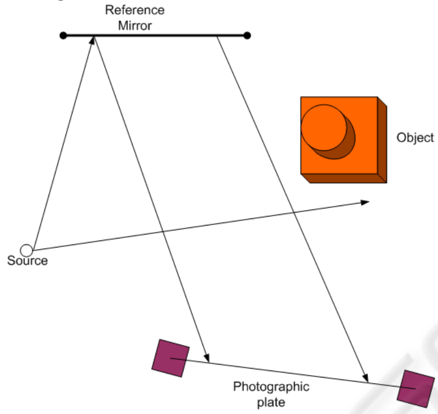

Figure 3: a) Capture of the hologram.

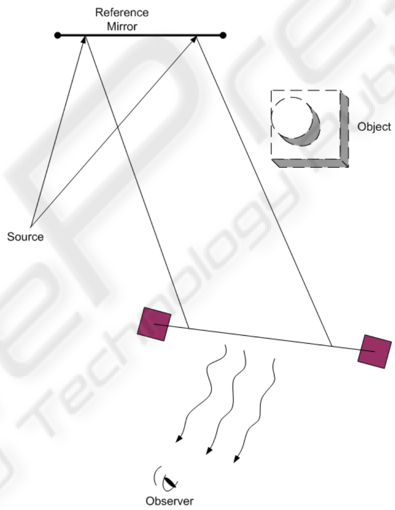

Figure 3: b) Observing the virtual image

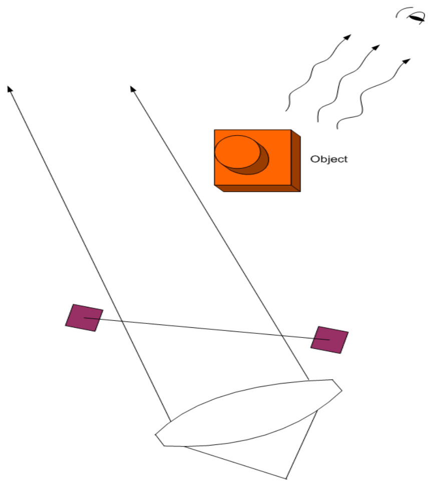

Figure 3c) Observing the real image.

Coherent light illuminates the scene of interest. A portion of the light is reflected from a mirror onto the photographic plate. This light reflected serves to form the 3D hologram of the object on the photographic plate by interfering with the light rays from the object. The reconstruction of the scene is carried out as follows; there are two possible configurations, one giving the virtual image and the other giving the real image.

To obtain the virtual image, the object is removed from the setup in figure 3a) and the photographic plate is illuminated by the same light source that was used while capturing. A virtual image of the object results as can be seen in Figure 3b). Lastly, if the photographic plate is illuminated from the opposite side i.e. different from the one that was used to capture the hologram, a real image of the object can be observed. These images both virtual and real are used in the reconstruction of objects in three dimensions (Goodman, C).

2.4 Conoscopic holography

Conoscopic holography is a relatively new non contact method used to reconstruct objects in three dimensions. It was discovered by Gabriel Sirat and Demetri Psaltis in 1985 as a modification to coherent holography for three dimensional data recording and imaging (Sirat, G., Psaltis, D., 1985). It is based on the propagation of light in anisotropic crystals. The property that enables the crystal to split the light rays into ordinary and extra ordinary rays is referred to as birefringence.

Birefringence is a property of certain crystals, which when a ray of light travels through their different optical axes, travels at different velocities. This behaviour is characteristic of anisotropic crystals given that they posses varying indices of refraction caused by the nature of the crystal lattice.

Having split the light ray into an extraordinary and ordinary beam they are made to interfere thus and give measurements of high precision.

Principle of operation

Consider a point source of light originating from an opaque object as is shown in figure 4. The conoscope comprises of the birefringent crystal, usually made of calcite, sandwiched between two circular polarizers. The recording of the holograms is done on a CCD matrix. This ray travels from the object towards the uniaxial crystal after penetrating the first circular polarizer. On entering the uniaxial crystal, the ray is divided in two, the ordinary and extraordinary.

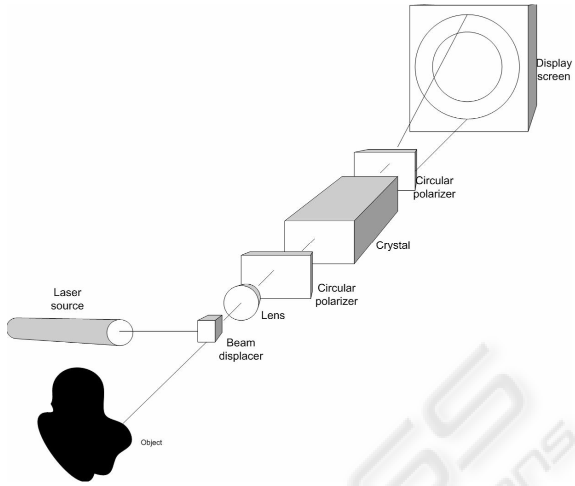

Figure 4: Conoscopic holography setup.

These rays are out of phase with each other and travel at different velocities within the crystal. At the other end of the crystal the ordinary and extraordinary rays are made to interfere after going through the second circular polarizer, which among other things returns both rays to the same phase. The resulting rays are made to interfere leading to either constructive or destructive interference. The resulting interference patterns are the conoscopic holograms and these contain the distance information that we are interested in. For a more detailed explanation of the principle with a mathematical foundation refer to (Sirat, G., 1992).

2.5 Moiré Interferometry

The term Moiré refers to an irregular wavy finish usually produced on a fabric by pressing between engraved rollers. In optics, it refers to a beat pattern produced between two gratings of approximately equal spacing. Moiré is a technique to study strains and deformations of structural elements with very high accuracy. It requires a highly stable environment and has mainly been a laboratory tool. Recently attempts have been made to develop a 3D scanner that uses moiré interferometry (Dubowsky, S). The method can be grouped under two major classifications that depend on the optical arrangement used: projection and shadow. Projection moiré involves the projection of a matching pair of gratings. The projection grating is placed in front of the light source and the reference grating is placed in front of the camera. The projected beam light is amplitude modulated with the pitch of the grating. When the beam falls on the surface of the object, the phase of the spatial carrier is modulated by the shape of the object surface. The

Table 1: 3D Scanners' parameters.

Company	**Type of scanner**	**Scanning technique**	**Working range (mm)**	**Speed (points/second)**	**Accuracy (mm)**	**Type of surface**
Konica Minolta	Vivid 700	Triangulation	600-25,000	n/a	0.11	Diffuse
Optimet	Conoline	Conoscopic holography	45	4,000	0.047	Diffuse to shiny
3D Scanners	MMZ	Laser Triangulation	50-150	n/a	0.1	Diffuse
Opton	Mini Moire scanner	Moiré interferometry	15	150,000	0.025	Diffuse to shiny
Roland DGA	Pix30	Laser Triangulation	0.2-406	n/a	n/a	Diffuse
3rdTech	Deltasphere 3000	Time of Flight	300-12,000	25,000	n/a	Diffuse
IQ instruments	CMMaster	Moiré interferometry	n/a	80,000	< 0.025	Diffuse to Shiny
Nub 3d	SIDIO	Laser Triangulation	700		0.08	Diffuse
Coherix	Shapix	Phase shifting interferometry	450	17,476	<0.02	Diffuse to shiny
Geodetic systems	Vstars(E4X)	Stereoscopy	n/a	n/a	0.008	Diffuse
Faro Technologies	Faro laser scanner	Interferometry	120,000	120,000	0.025	Diffuse to shiny
Brueckmann	OptoTOP-HE	Structured light	25-400	1,555,555	0.045-0.45	Diffuse
Perceptron	Scanworks	Laser Triangulation	23-71	23,040	0.035	Diffuse

reference grating is phase shifted against the projection grating.

Shadow moiré involves positioning a grating close to an object and observing its shadow on the object through the same grating. Moiré is considered a very good method for 3D reconstructions because it amplifies small errors, thus enabling their detection. It requires less computer time, and so has a great potential for rapid online registration and inspection. The parameters of a moiré can easily be changed. Moiré however has not been fully exploited owing to the difficulties encountered in designing and adjusting a system based on it.

In moiré interferometry, light is projected onto an object's surface through two equally spaced fringes. The resulting patterns are viewed at an angle different from that at which the fringes are projected. The contour interval depends on the spacing of the fringes projected on the surface and the projection viewing angle. A detailed mathematical analysis of the formation of the moiré fringes may be found in (Creath, K., Wyant, J).

3 COMPARISON OF 3D SCANNERS ON THE MARKET

The manufacturers of 3D scanning equipment can be grouped in three categories; those that provide the hardware, those that write the software and those that implement both systems. We looked at the leading manufactures of 3D scanners and this enabled us to make a comparison of their various products. Given that these use different technologies these results are not easily compared since we have to identify uniform parameters for comparison in each of the methods. Owing to the variations in software available on the market, the survey has been limited to the comparison of the hardware and its performance. Definitely their performance depends greatly on the software, but that will be dealt with in another article.

The providers of scanners that we have been able to identify, that use each of the various technologies for 3D reconstruction are diverse. A look is taken at those who provide the datasheets on their products. Using these, a comparison of similar parameters is carried out to come up with unbiased conclusions.

The scanners are commercial implying that we have had to rely on the information provided by their manufacturers, as it is close to impossible to have all scanners in the university laboratory considering their high cost. The parameters taken into consideration were; the operating range, accuracy, speed of capture, and the types of surfaces. Each scanner will be compared with a series of cameras in the same range. This will be followed by a comparison of with the results from other scanning techniques. The survey looked at products from the following companies: 3D Scanners (MMZ), Konica Minolta (VIVID 700), Optimet technologies (Conoline), Opton formerly EOIS (Moiré scanners), Roland (Pix 30) among others.

Table 1. shows these parameters in several commercial scanners. Judging from the results presented, several observations about the various technologies can be made. Laser triangulation is the commonest method used in 3D scanners, as seen in the table most scanners use triangulation. The reasons that are put forward for its popularity are; it's easy setup, its low cost as compared to other methods, its speed which enables real time scans and reconstructions on the production line. Laser triangulation is limited when very high precision and accuracy are required. It is also marred by speckle and inability to scan reflective surfaces.

Stereo is passive and does not emit any radio or light energy. Recording on site can be done very fast and as such it can be used on-line. However, the matching of the points in the two images captured by the cameras in stereo is tedious. Whereas they can adjust for component size, stereo cannot easily accommodate free form surfaces. In addition, the requirement for one of the two cameras to be fixed at a specific angle restricts the inspection region and presents difficulty in inspecting the entire component. The scene has to be rigid to begin reconstruction which makes it difficult for on-line implementation.

Moiré is considered a very good method for 3D reconstructions because it amplifies small errors, thus enabling their detection. It requires less computer time than other methods like laser triangulation during capture, once it has been properly setup, and so has a great potential for rapid on-line registration and inspection. The parameters of a moiré can easily be changed. Moiré limitations can be cited in the difficulty in its design and in adjusting the setup to capture data. Its very high precision makes the acquisition costs extremely prohibitive (Dubowsky , S).

Holography performs much better than laser triangulation when it comes to precision and accuracy. Readings of up to several microns can be taken. However it is limited as far as speed is concerned. A lot of precaution has to be taken when recording the holograms since lengthy exposure requires a high level of stability in order to obtain good results in the processing. The range for recording the holograms also has to be well chosen in order to get a good reconstruction. Holography has not been fully taken on in industry inspite of being very accurate, given the complication in adjustments that have to be made while taking readings.

Conoscopic holography being a modification to holography sorts out the speed problem. It features a high precision in its readings and reconstructions of up to 47 microns using an objective of focal length 100mm. The accuracy and range depend on the objectives used on the conoline. Conoscopic holography has clearly enabled holography to be applied to the manufacturing industry. Of the benefits we are able to note using the conoline is the ability to measure several surfaces and reach an angle of incidence up to 85º, which not many methods are capable of doing. Conoscopic holography could still benefit from an increase in its speed of capture in order to be adapted to more real time applications. (Optimet)

4 CONCLUSIONS

Having looked at the various methods of 3D reconstruction, we hereby are able to reach a decision on which technology to be used in our 3D scanner. The pros and cons of each and every method have been expounded, in order to serve as an aid to all those wishing to implement scanning processes for both experimental and industrial purposes.

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