Developments in Three-Dimensional Scanning Techniques and Scanners

Varun Batra and Vijay Kumar

Abstract Three-dimensional scanning is increasingly used in numerous domains such as medicine, computer graphics, and architecture. The first three-dimensional scanning technology was evolved in the 1960s. There are an immense variety of methods to scan objects and their assortment depends primarily on the type of the object and its location. The objective of this study is to provide an overview of three-dimensional scanning technologies and methodologies which were projected in the existing industrial as well as scientific literature. All through the paper, basic physics of surface reflectivity and a variety of related techniques are reviewed, which consist, mainly, of laser scanning and photogrammetry, as well as the three-dimensional scanners, augmented with combinational and comparative studies. These studies are helpful for intending to make a clearer distinction on the relevance and reliability of the possible preferences.

Keywords 3D scanning · Triangulation · Time of flight

1 Introduction

Three-dimensional scanning technology evolutes during the latter half of the twentieth century in an endeavor for accurately recreation of the surfaces for various places and objects. The technology has copious applications and entailing various magnitudes of object scale. These embrace reverse engineering [1, 2], validation of product quality [3], digitally preserving historical artifacts [4, 5], medical applications [6–9], assessing the bearing capacity of slab concrete [10], turbine blades [11], etc. Fundamentally, three-dimensional scanning is the act of confining the data from factual world and bringing that same into the digital conduit which in result gives the cloud of points. Several images or scans, depending on the technique, are brought

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into a common reference system where they are merged to form a comprehensive model known as alignment [12]. Cameras and three-dimensional scanners are very akin to each other. Similar to cameras, three-dimensional scanners also have a conical field of view and are only able to gather information about the surfaces which are not veiled. Whereas the camera gathers the color information and three-dimensional scanner gathers the information of distance, regarding the surfaces of subjects within its field of view.

The first three-dimensional scanning technology was established in the 1960s. The advent of computers makes it feasible to build up a vastly complex model, but there is a hitch in creation of that model. Subjects having complex surfaces defied the tape measure, so in 1980s, the tool-making industry built up a contact probe which allowed the creation of precise model, although it was quite slow. The endeavor was to develop a technology, which gathers the equal amount of information but at higher speed, resulting in a more valuable application. These lead professionals to initiate the development of optical technology, because the use of light was much faster than a physical probe. This will enable the scanning of soft objects, which would be susceptible to prodding. After 1985, the contact ones were replaced with three-dimensional scanners that could use the optical technology which involves lasers and white light to capture a given subject surface [13].

This paper will first discuss the different techniques involved in three-dimensional scanning of the object. This will be augmented by an overview of basic physics of surface reflectivity and different range measurement principles implicated in laser scanning. The third section briefly outlines the three-dimensional scanners of different types operating on different principles. The fourth section constitutes the comparative study of various techniques and instruments involved in three-dimensional scanning. The fifth section will describe the diverse applications of three-dimensional scanning.

2 Three-Dimensional Scanning Techniques

For digitally attaining the profile of a three-dimensional subject, there are copious techniques. A well-established categorization [14] categorizes them into two categories: contact and non-contact three-dimensional scanning techniques [15]. As well there are numerous techniques which are fall underneath these techniques.

2.1 Contact Technique

Contact three-dimensional scanning techniques are those which will probe the subject by making a physical contact with the subject itself. The probing of the subject is done

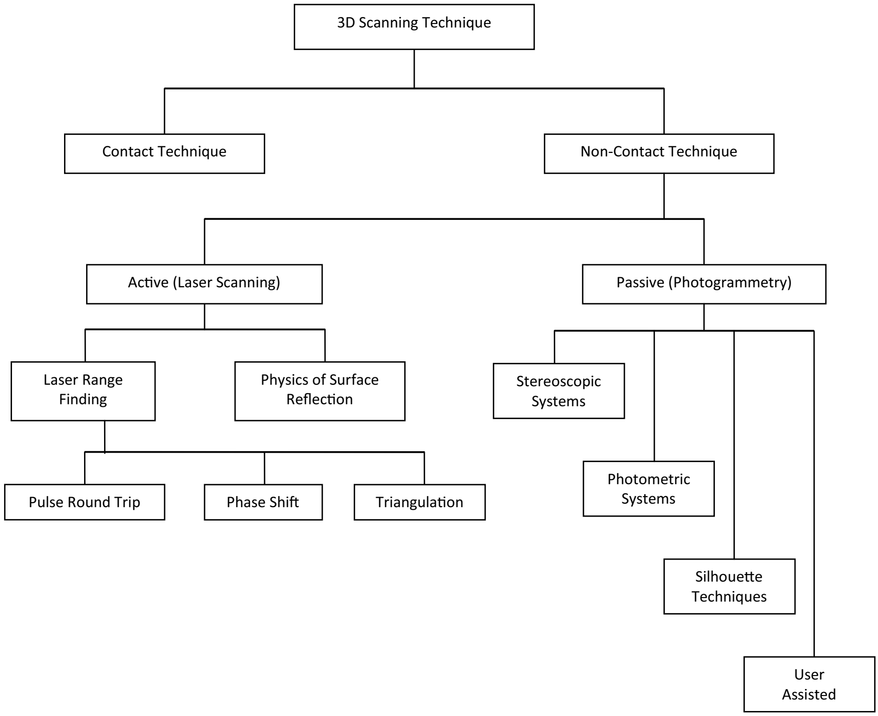


Fig. 1 Categorization of three-dimensional scanning techniques

with the help of robotic arm or manual arm at end of which the probe is available. As the probe touches the surface of the subject, position of the probe recorded and system gets the information of subject (Fig. 1).

2.2 Non-Contact Technique

In this technique, the three-dimensional scanning of the subject is done by without making any physical contact with subject; more appropriately will say the use of an optical technology to probe the subject. In this, the probing is done either by the white light or a beam of laser or ambient light which are projected against the subject's surface. Non-contact three-dimensional scanning technique is further classified [16] into two techniques, i.e., active and passive.

Non-contact active technique. Active non-contact three-dimensional technique radiates the subject with energy and detects the change in behavior of radiated energy in order to probe the subject. In today's era, the most actively using technique to probe the subject is the three-dimensional laser scanning technique which falls under the category of non-contact active technique.

Laser scanning is the technique that gathers three-dimensional coordinates of a subject in a given region at a high rate without human intervention with a systematic pattern and achieving the results in factual instance by using laser device. Laser range finding is the term that involves the aspect of distance measurement, which relies on laser light for performing that particular measurement. The complete technique entails the surface reflectivity physics [17] and some principles involved in laser range finding [18] are discussed in the sections below.

Physics of surface reflection. Electromagnetic radiation involving laser and light demonstrates the properties of both particles and waves. The characterization of electromagnetic radiations is done by a frequency, amplitude and wavelength. The nature of radiation is examined with the help of their relationship between frequency and wavelength of electromagnetic radiation. The electromagnetic waves have a property that all electromagnetic waves have same speed in the vacuum. As described in Eq. 1, the speed of wave is dependent upon frequency and wavelength, clearly helps in characterization of wave:

$$c = f\lambda \tag{1}$$

where c = speed of light, f = frequency of radiation, λ = wavelength of radiation.

Equation 2 describes that light is prepared by photons that possess no mass and also shows that energy (E) is relative to the wavelength (λ) of electromagnetic radiation:

$$E = \frac{hc}{\lambda} \tag{2}$$

where h = Plank's constant.

The standard categorization of electromagnetic radiations specifically based on wavelength as shown in Fig. 2. From the figure, we observe that the range of lasers falls into both the ultraviolet and infrared parts of the spectrum as well as some lasers exhibit in visible region of spectrum. The different wavelength lasers are developed and used for various applications. Lasers are categorized into semiconductor diode, solid state, gas, and dye lasers. Each laser has different mode of operation that is continuous and pulsed, some of them exhibit only pulsed mode and some exhibit both. Some of the lasers are shown on the electromagnetic spectrum with their respective wavelengths in micrometers (μm).

Natural light comprises of an abundant wavelengths. When this light with random emission paths strikes the surface of a subject, amount of an electromagnetic radiation gets reflected by it. The fraction of radiation reflected to the quantity formerly received at the subject surface is practically defined as reflection. A subject surface exhibits various properties in contrast with incident radiation; surface may reflect, transmit, or absorb the incident radiation. There are varieties of surfaces that we deal in our daily life; all those will show the different reflection behavior depending on their surface roughness. When the roughness of surface is lesser than the incident radiation wavelength, this surface will perform the specular reflection where the

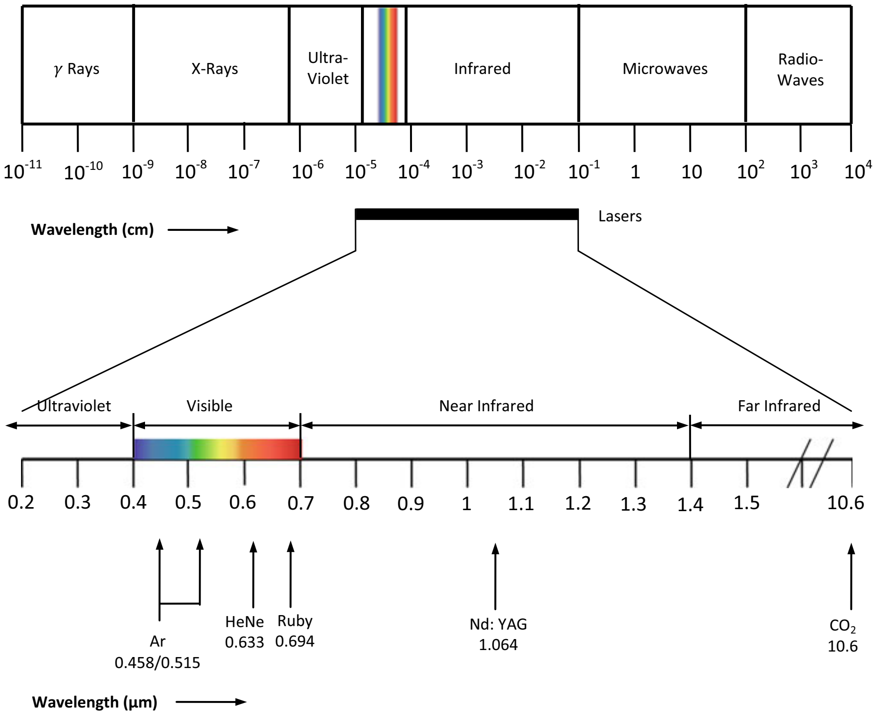


Fig. 2 Wavelength-based classification of electromagnetic radiations

angle of incidence is equal to angle reflection as shown in Fig. 3a. Similarly, when the roughness of surface is greater than the incident radiation wavelength that surface will perform the diffuse reflection as shown in Fig. 3b. Most of the surfaces in the natural atmosphere demonstrate the combination of specular and diffuse reflection known as a mixed reflection as shown in Fig. 3c.

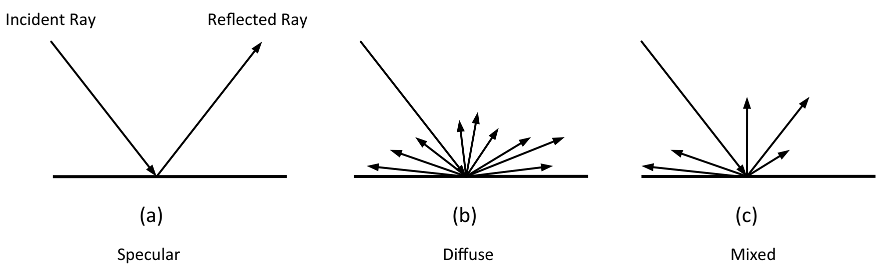


Fig. 3 Reflection types:**a** Specular,**b** diffuse, and**c** mixed

Laser range finding. There are different ranging principles that can be used to compute the distance amid sensing device and subject. These different ranging principles are based on the optical time of flight technique and triangulation technique. These principles have different precision and range perimeter. Optical time of flight is the round trip estimation of a light wave emitted from the emitter to the targeted subject, and then reflected from the subject back to the receiver. It is classified into two types: direct and indirect time of flight. The probing of longer ranges can be done by using the measurement principle of direct time of flight also known as pulse round trip time obtaining the centimeter accuracy. The more precise system of measurement which is fast and accurate than the former but limit to shorter distances of hundred meters is indirect time of flight or phase shift measurement technique. The higher precision and accuracy from the latter technique is also developed known as triangulation which is constrained to smaller distances. These ranging principles detailed below.

Pulse round trip time (Direct time of flight). It is a measure of the time delay between the light pulse sent and received using a time-to-digital converter. The light pulses are typically very short and high intensity. In pulse round trip measurement, a laser pulse is emitted by using a semiconductor or solid-state laser as shown in Fig. 4. The emitted pulse is allowed to pass through the environment, and while traveling through it, laser pulse interacts with surface of subject that comes in its path. The incident laser pulse has energy package associated with it, which can be absorbed or reflected depending on the surface of subject. If laser pulse is reflected, then it will follow the law of reflectivity which we are already discussed. The reflected laser pulse from the surface will then be captivated by receiver. The influence of subject surface on the laser pulse character is shown in Fig. 5. Upon emission of the laser

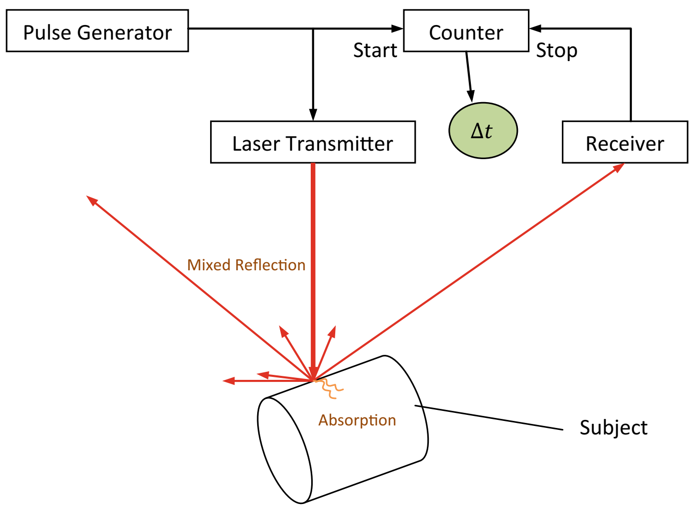


Fig. 4 Pulse round trip measurement principle

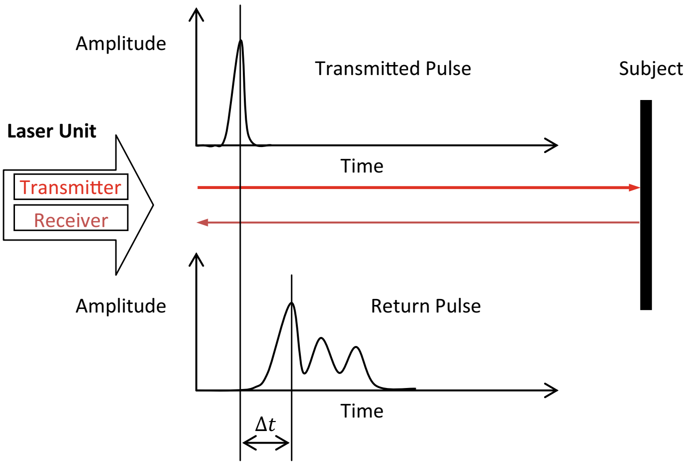


Fig. 5 Subject's surface influence on laser pulse

pulse, a time counter begins and ends after receiving the reflected pulse. If the interval of time is Δt, and c is the velocity of the light amid pulse emitter and subject, the range (r)

$$r = \frac{c\Delta t}{2}$$

Phase shift (Indirect time of flight). This technique uses periodic, low intensity, modulated light pulses. The periodicity of the pulses is determined by the modulation frequency. The phase delay among the transmitted light and the reflected light represents the round trip distance to the subject which is measured by the signal processing pipeline as shown in Fig. 6. Since the signal processing is done in the frequency domain, several cycles of that low intensity periodic pulses are required to complete a single measurement. The measurements which can be done by high frequency modulation will result in precise distances but will constraint to smaller distances. If phase shift among the signal emitted and received is φ, and c is the velocity of the light between the path from emitter to subject and the modulated frequency f_m, the range (r)

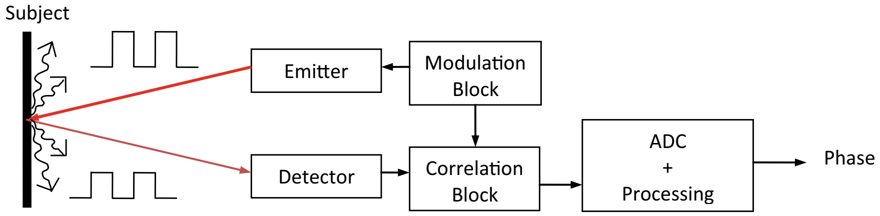


Fig. 6 Indirect time of flight principle

$$r = \frac{c\varphi}{4\pi f_m}$$

When using indirect time of flight, there is a distance, where the phase shift among the signal emitted and the signal received is greater than or equal to the emitter period. This is referred to as aliasing as the two different signals become indistinguishable. To find the maximum range or maximum distance before aliasing occurs as shown in Fig. 7, the formula is:

$$\text{Max Range} = \frac{c}{2f_m}$$

If the target is further than the max range, steps must be taken in order to de-aliasing their signals. If de-aliasing of signals is not performed, ambiguity in distance measurement can be attained due to periodic variation in phase as the distance is increased above the max range [19]. The removal of vagueness can be easily attained by measuring through two dissimilar modulation frequencies. The approach

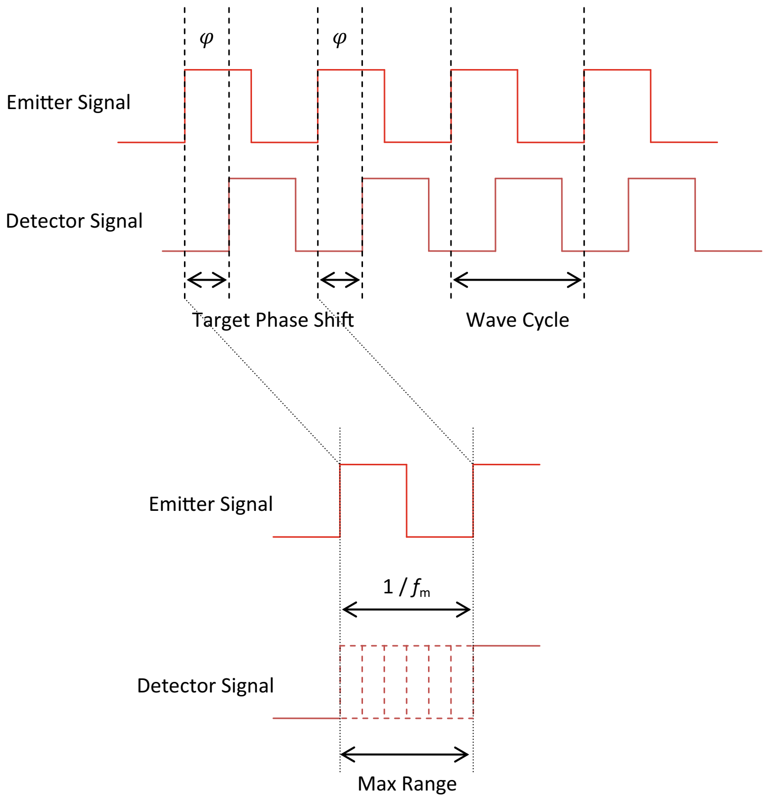


Fig. 7 Showing maximum range before aliasing

of frequency discriminatory computation of the phase variations among emitter and receiver helps to determine the precise measurements [20]. The scanning rate, using indirect time of flight technique, is much quicker than using the direct time of flight technique. The output or point of cloud attained from the indirect time of flight is noisier than the direct time of flight technique [21].

Triangulation. The optical methods which include triangulation technique are the methods based on contactless light reflected from the object and determine its geometry by means of a light-sensitive detector. Active optical methods rely on the projections, so to study the reflected light observations. The active optical method is based upon laser triangulation beam projection. Triangulation-based laser scanning technique was initially developed at National Research Council of Canada in 1978 [22].

For probing subject, the measuring system using method of laser triangulation comprises the laser light as a source (in the form of point or line), and the subject measuring light-sensitive receiver, most commonly uses a camera [23]. The laser beam projected on the surface of subject and by making use of a light-sensitive receiver to seem for the position of dot of the laser. Depending upon the distance from which the laser beam is striking on the subject's surface, dot of the laser emerges at dissimilar positions in the receiver's field of view. The technique named as laser triangulation for the reason that the laser emitter, the camera, and the dot of laser collectively stature a triangle as shown in Fig. 8. The measurement system consists of a laser line and the camera mounted on stand. The distance between the camera and laser beam projector provides one of the length dimensions of triangle. The angle between the plane of the laser beam and the plane perpendicular to the camera image is known. With these pieces of information, distance of dot of laser (measuring point) from the receiver (camera lens) is determined. A stripe of laser is more desired over the dot of laser, as it would sweep around the subject for probing and helps in speeding up the data acquirement process.

Non-contact passive technique. Passive non-contact three-dimensional technique does not radiates the subject with energy; instead rely on detecting ambient

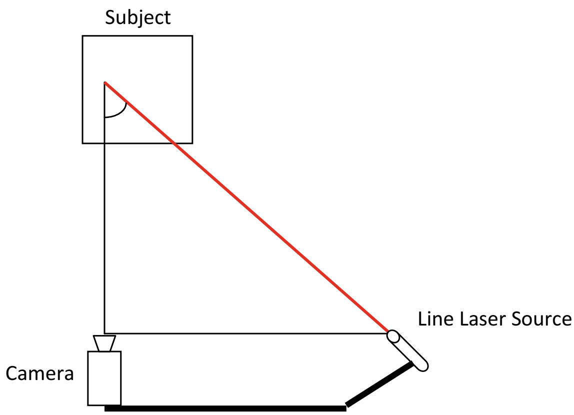
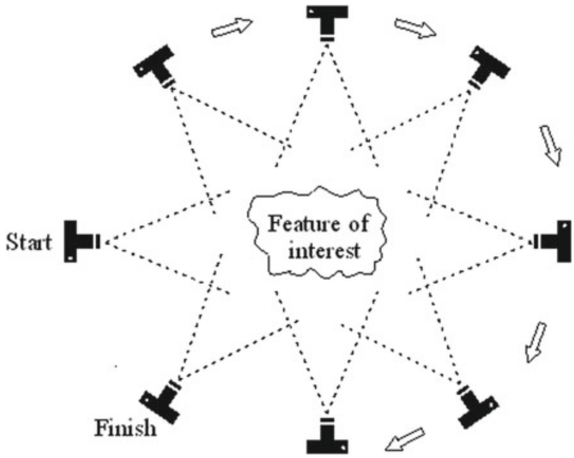


Fig. 8 Principle of a laser triangulation

Fig. 9 Principle of photogrammetry



radiation in order to probe the subject. This technique uses the visible light for probing as it is an eagerly existing ambient radiation. This involves the technique of photogrammetry to replicate the subject.

Photogrammetry technique. Photogrammetry is the science of making measurements from photographs [24]. Photogrammetry technique is defined as the technology of gaining the useful information about the substantial subjects and surroundings during the procedure of interpreting photographic images, measuring and recording. This technique uses methods from different disciplines, mainly projective geometry and optics. The principle behind photogrammetry is capturing the numerous images of the subject from different sights and importantly having a common point of reference in each photograph as shown in Fig. 9. The subject which needs to be developed is placed at a well luminosity position. The set of images are then put up into any photogrammetry application software to develop a three-dimensional model of the subject as an end product. There are some systems and techniques which are using the photogrammetry principle are discussed in section below.

Stereoscopic systems. These systems are generally using the two video cameras which are faintly spaced out from each other and both looking at the same scenario. Examining the trivial difference among the digital images perceived by both the cameras makes it feasible for determining the distance at every point in the images.

Photometric systems. These systems are typically using a single camera, apart from numerous shots of digital images are taken underneath the changeable lighting situations. In an attempt to recuperate the orientation of surface at each pixel, these techniques capsize the image formation model.

Silhouette techniques. These techniques are using outlines produced by the series of photographs about a three-dimensional subject which is contiguous to a contrasted surrounding. The visual hull approximation of subject is attained by the intersection

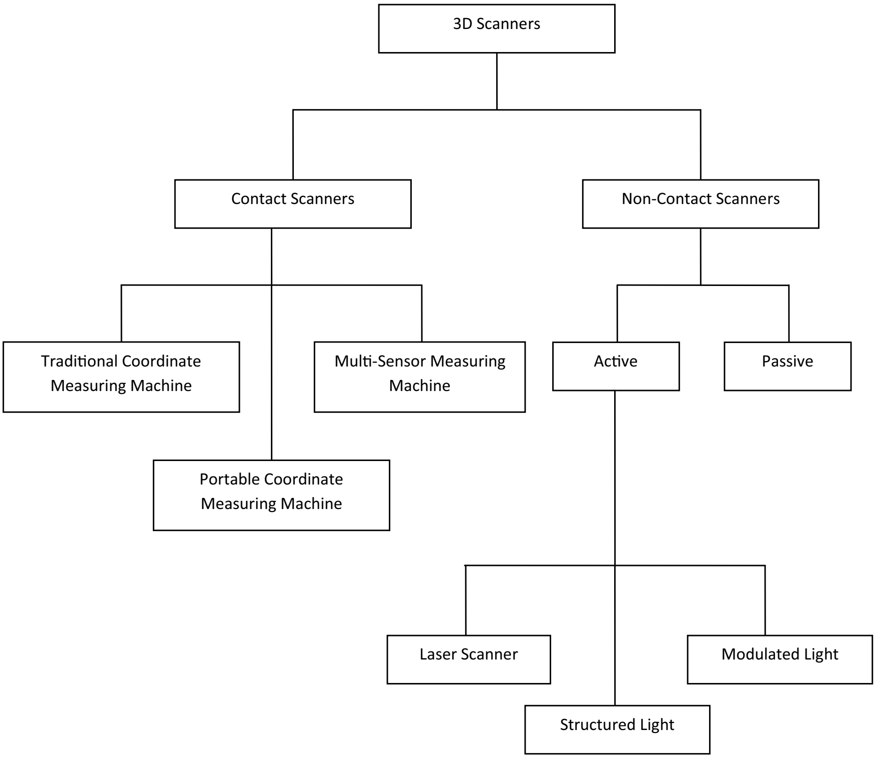


Fig. 10 Categorization of three-dimensional scanners

of those extruded silhouettes. The drawback of using this approach is, sometimes the concavities of the subject are unable to detect.

User assisted (Image-based modeling). These are the methods which are based on the assistance of user for the purpose of identifying and detecting some of the features as well as shapes from a set of various digital pictures of a subject. Then the resulting assistance would help in building the approximated model of the subject itself. Building a quick approximation of simple-shaped subjects is the useful perspective of this technique.

3 Three-Dimensional Scanners

Three-dimensional scanners are the devices which are used to capture the physical objects from factual world as well as surroundings in some scenarios, so that the captured object can be remodeled or analyzed digitally along with getting the complete or partial 3D measurement of subject. The majority of these devices generate an output of highly dense point cloud. There are numerous scanning equipments for digitally attaining the profile of a three-dimensional subject. A well-established categorization [25] categorizes them into two types: contact and non-contact three-dimensional scanners. Non-contact three-dimensional scanners are further categorizing into two main categories, active three-dimensional scanners and passive three-dimensional scanners. There are varieties of scanning equipments that fall underneath these categories (Fig. 10).

3.1 Contact Three-Dimensional Scanner

Contact three-dimensional scanners are normally attuned to operate on the rigid podium which consists of an articulated mechanical arm at the end of which the probe is attached. This articulated arm can be manipulated over the surface of subject either robotically or manually. The moment probe makes a contact with the surface of subject; there is some position of the arm from which the probing point is determined and the same recorded by scanner. The recorded positions at different points of a subject form a point cloud. The highly accurate contact three-dimensional scanners called coordinate measuring machines (CMM's). These kinds of contact three-dimensional scanners are often used by the manufacturing industry for inspection rationale. Contact three-dimensional scanners are not a suitable choice for the delicate subjects because the probing may deform or else damage the surface of subject as well as these scanners undergoes very slow scanning speed. The various scanners are fall under this category are discussed in section below.

Traditional coordinate measuring machine (CMM). A traditional coordinate measuring machine (CMM) is a three-dimensional contact scanner for assessing the physical geometrical characteristics of the subject. The scanner can be operated manually or controlled through application software installed on system software. Probes are the tools which consist of a shaft at the end of which a small ball of known radius is attached as well as the dimensions are defined by attaching the same to scanner. The coordinate measuring machine is subsequently programmed to probe the subject. The positional measurements are recorded by the scanner after the scanner senses the contact of probe on the surface of subject.

The most common type of traditional coordinate measuring machine is a viaduct type which consists of three axis x, y, and z. The probing system of scanner endows with six degrees of freedom. When the accuracy and precision is the primary perimeter to attained in the output, these coordinate measuring machines are separately deployed in a control room which consists of reinforced floor, vibration isolated system, controlled environmental conditions and must not have forces which affect the accuracy. Moreover, most coordinate measuring machines have a rigid and perfectly leveled granite base at which the subject is fixed so to constrain the movement of the subject (Fig. 11).

Portable coordinate measuring machines. Portable coordinate measuring machines are quite analogous to traditional coordinate measuring machines in the

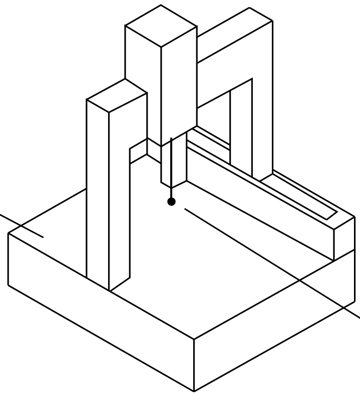
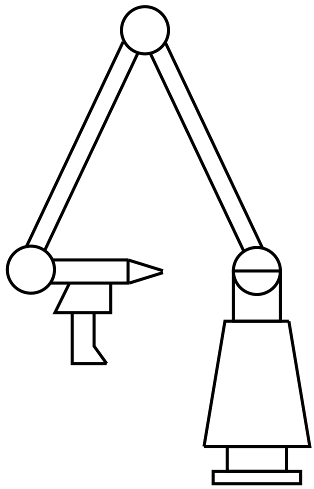


Fig. 11 Traditional coordinate measuring machine

verity that it also uses the touch probe to digitally acquire a subject. The portable coordinate measuring machines are using a ball or point probe on an articulating arm, allowing the users to collect individual three-dimensional data points from the physical object. These articulating arms have several rotary axis with rotary encoders, instead of linear axis. The advantages of these portable arms are that these are light in weight and can be carried and used anywhere. These scanners are always requiring a human for its use, and the overall efficiency is less accurate than the traditional coordinate measuring machines. These measuring machines are required to be fixed on a rigid surface, subsequently to make the arrangement prone to vibrations and other surrounding constraints which will affect the quality and performance of the machine. These machines also lack in flexibility in terms of the shape of the subject to probe as well as the location where the arm is fixed (Fig. 12).

Fig. 12 Portable coordinate measuring machine



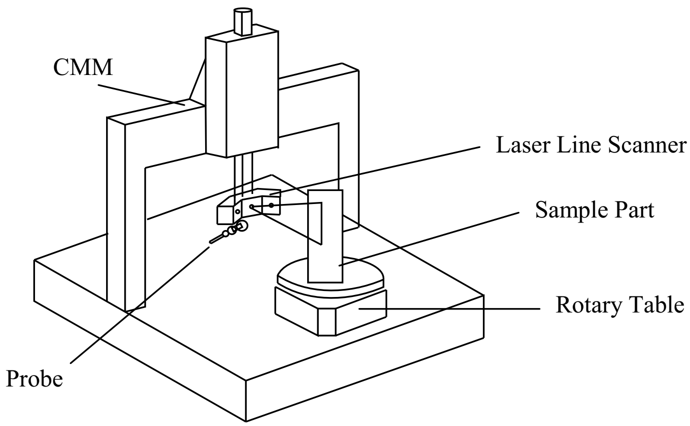


Fig. 13 Multi-sensor measuring machine

Multi-sensor measuring machines. The technology of traditional coordinate measuring machines is making use of the touch probes for the measurement. The same setup evolutes with other measurement technology or we can say optical technology. This combined arrangement of touch probe and optical technology which constitutes laser and white light sensors develops a machine known as multi-sensor measurement machines (Fig. 13).

3.2 Non-Contact Three-Dimensional Scanner

Non-contact three-dimensional scanners justified by its name itself that an arrangement does not make any physical contact with the subject's surface to digitally acquire the same. Non-contact three-dimensional scanners are further categorizing into two techniques, i.e., active and passive techniques to digitally acquire the subject. The ultimate outcomes of these scanners are the highly accurate and dense cloud of points which can be further used for numerous applications like rapid prototyping and feature or surface inspection.

Non-contact active scanners. Non-contact three-dimensional active scanners radiate the subject with energy and detect the change in the behavior of radiated energy in desire to digitally acquire the subject or environment. The possible radiations which employs on the subject for probing are electromagnetic radiations, from which ultrasound, x-ray, light, and laser are the most predominantly using nowadays. The frequently used non-contact three-dimensional active scanners embraces three-dimensional laser scanners, structured light scanners and modulated light scanners as well as some volumetric techniques that are computed tomography scanners and magnetic resonance imaging scanners. Several existing non-contact active scanners are discussed in the sections below.

Three-dimensional laser scanners. Three-dimensional laser scanners, as the name implies, do make use of the laser for scanning or probing the subject's surface. The basic principles behind the laser scanners are that they emanate and entertain their own electromagnetic radiation for probing the surface of subject. The term laser scanner encloses a variety of instruments that functions on different principles as well as in different surroundings along with different levels of accuracy and precision. Most of the laser scanners functions on any of three laser ranging principles: pulse round trip time (direct time of flight), phase shift (indirect time of flight), or triangulation. The data referred to as a collection of points converted from angular and range measurements into a universal Cartesian coordinate system that delineates the subject's surface in immense detail. This data collection can be done with different laser scanners, importantly classifies into four types on the basis of their orientation that are: terrestrial scanners, airborne scanners, mobile scanners, handheld scanners. The laser scanning systems with typical accuracies and ranges with the usage are detailed in the table given in [24].

Structured light scanners. Structured light three-dimensional scanners emanate a pattern of electromagnetic radiation, usually light is used, onto a subject and look at the distorted pattern of light after hitting the subject. The three-dimensional models can be built by altering the light patterns and view angles. Either a sweeping laser or the LCD projector is used for projection of one-dimensional light onto the subject. The pattern projector and camera are aligned, angled, and calibrated to one another. A camera seems the character of the distorted light pattern and uses a range finding technique of triangulation or any other algorithm for calculating the distance of each point on the distorted pattern or in line as shown in Fig. 14. The pattern of emitted light is categorized into one-dimensional pattern and two-dimensional pattern. The arrangement in which line is probing the subject is one-dimensional light pattern scanning, and on the other hand, if it is probed with the grid or line stripe, pattern is the two-dimensional pattern scanning. The laser stripe ambiguity comes to scenario

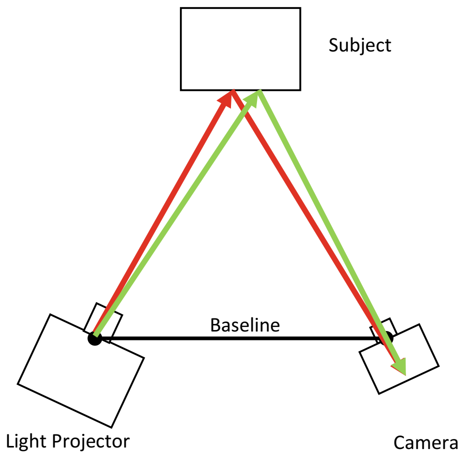


Fig. 14 Working of structured light scanner (Top down view)

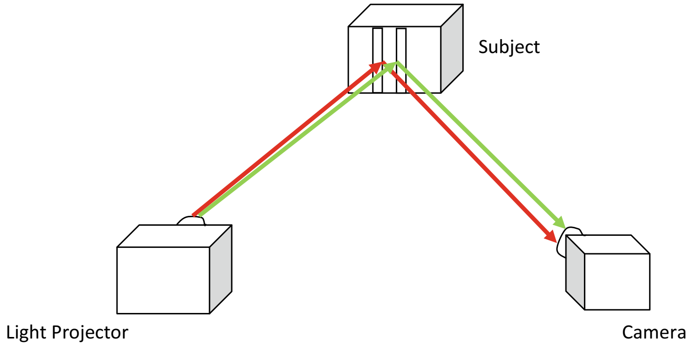


Fig. 15 Working of structured light scanner (Angled view)

in the cases where the subjects profile is containing holes, rapid change in depths and occlusions; these parameters either break down the stripe sequencing or may hide the stripe. This ambiguity can be resolved using multi-stripe laser triangulation algorithms.

The advantages of structured light scanners deliver an admirable resolution and good quality data, which enables it to capture the smallest detail or feature available on the subject's surface. The limitation as we know these scanners can acquire a good quality data in addition to that they also acquire the good quantity data in one scan. The subject replica development requires a multiple scans that are very time consuming, which denotes that the scanning speed is not enhanced by this methodology (Fig. 15).

Modulated light scanners. The modulated light three-dimensional scanners illuminate a persistently altering light on the subject. Generally, the light source has a cycle whose amplitude portrays a sinusoidal pattern. The reflected light is detected by the camera which measures the importance of light variation and find out the distance traveled by light. The modulated light moreover allocates the three-dimensional scanner arrangement to disregard the light from other sources except laser, so to avoid any obstruction.

Non-Contact Passive Scanners. Non-contact passive scanners cannot emanate any sort of radiations on subject for probing, but instead dependent on perceiving reflected ambient radiation. Most of the passive scanners perceive visible light because it is an eagerly presented ambient radiation. The other type of radiations possibly will use infrared radiations. Passive scanning methods are quite economical due to no need of particular hardware requirement, only required is digital camera. Some non-contact three-dimensional scanners include stereoscopic scanners, silhouette scanners, etc.

4 Discussion

The three-dimensional scanning techniques and instruments compose an extensively broad range; due to this fact, several studies have performed to contrast them from diverse perspectives.

4.1 A Comparison of Active and Passive Scanning Technique

In [26], the comparison for data attainment and processing from three-dimensional scanning techniques, i.e., passive and active, were discussed. In this overview, majorly the laser scanning in active technique and photogrammetry in passive technique are reviewed. Initially for data acquisition, the laser scanning senses through point sensors with polar geometry, whereas photogrammetry senses with linear or framed sensors with perspective geometry. As the subject is radiated with laser directly, it is a direct acquisition in active technique, whereas there is neither any direct contact with subject surface nor by any optical technology so it is an indirect acquisition in passive technique. The active technique is founded to be lesser in flexibility and variability and vice versa in case of passive techniques. Active technique would efficient at lower flying speed and height, whereas passive technique gives efficient outcome at higher flying speed and height. Last but not the least, the active technique is proved somewhat automatic and passive technique requires a manual intervention.

4.2 Three-Dimensional Scanning Instrument

The various three-dimensional scanners are studied in the third section, from where we conclude that each scanner has advantages and disadvantages in perspective of range, accuracy, and precision. So, it is not feasible that each scanner will able to perform in all scanning situations. The scanning devices are broadly categorized into three categories on the basis of range [27] that are 10 to 100 cm, 100 to 1000 cm, and 1000 to 10,000 cm. More importantly, when rate of scanning or point acquisition speed taken into the account for looking into the practical use of three-dimensional instrument, this parameter can increase or decrease the operational time for digitally acquiring the subject or surroundings. Usually, the scanning resolutions of higher resolution are desirable. Every three-dimensional scanner has its own limited field of view. Larger is the field of view of scanner, larger is the data collected by scanner in the single scan. Portability factor is to be present in every scanner for the ease of transportation as well as their use.

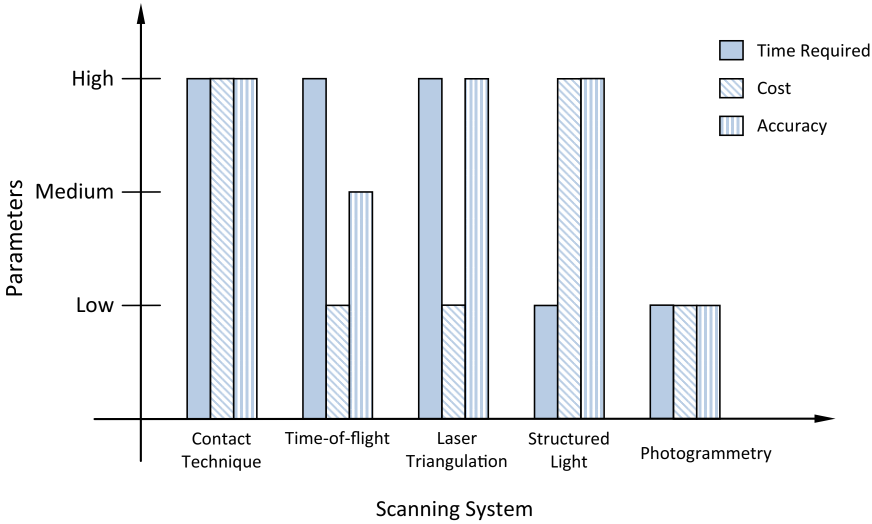


Fig. 16 Parameter-based comparison

4.3 Metric Survey

In terms of size and complexity, Fig. 16 attempts to differentiate between the available techniques to guide the user toward an appropriate decision [28]. Hand measurements are able to provide the dimensions of the small objects at finite number of points and become uneconomic for larger size objects. Total station theodolites (TSTs) are the instruments used in data collection as well as for survey of site control network. A global navigation satellite system (GNSS) is generally used for geographic information system (GIS) data collection and topographic task. GNSS is also used to measure control networks, especially when connecting to a national grid. Photogrammetry and laser scanning are the techniques which are collecting the data from the object in abundance and are found appropriate techniques for scanning the compound subjects over a variety of scales (Figs. 17, 18, 19 and 20).

4.4 A Comparison of Laser Range Finders

The various three-dimensional scanning techniques are studied in the second section, from where we conclude that each technique has associated benefits and limitations which make them apposite for diverse situations. Here, we discuss some of them for laser range finders that are time of flight and triangulation range finders. The time-of-flight range finders have an advantage that this technique allows to use for amazingly long distances, about thousands of meters [29]. This principle is therefore suitable for

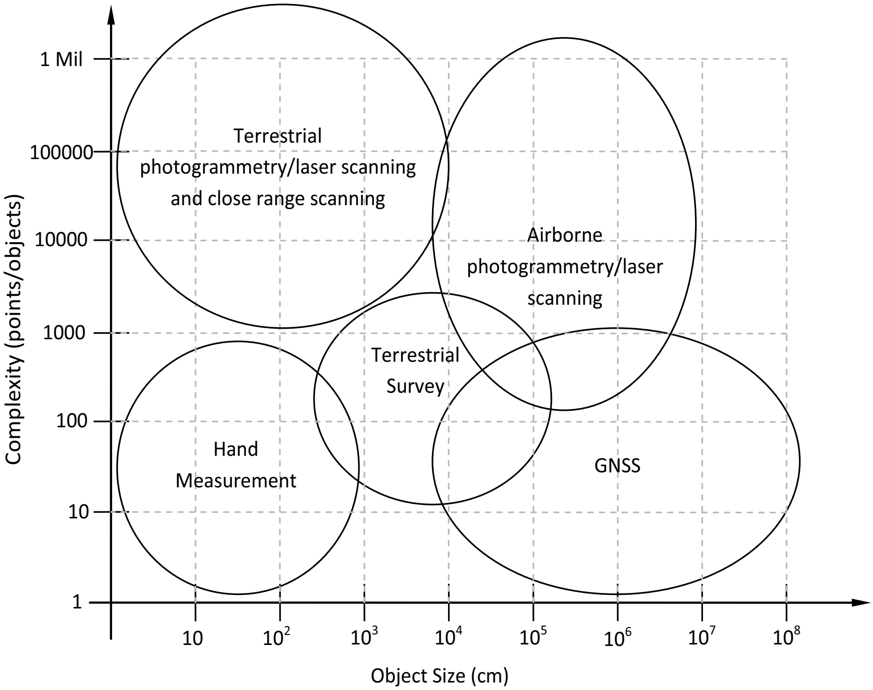


Fig. 17 Appropriate technique selection through size and complexity

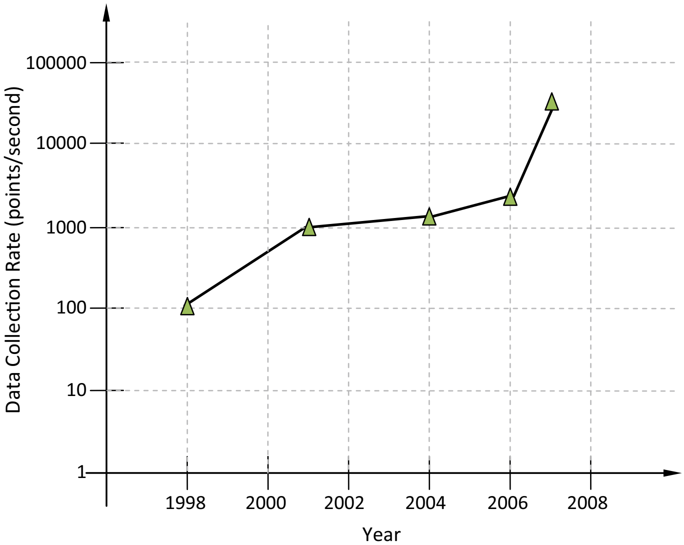


Fig. 18 Showing evolution of terrestrial pulsed laser scanning technology

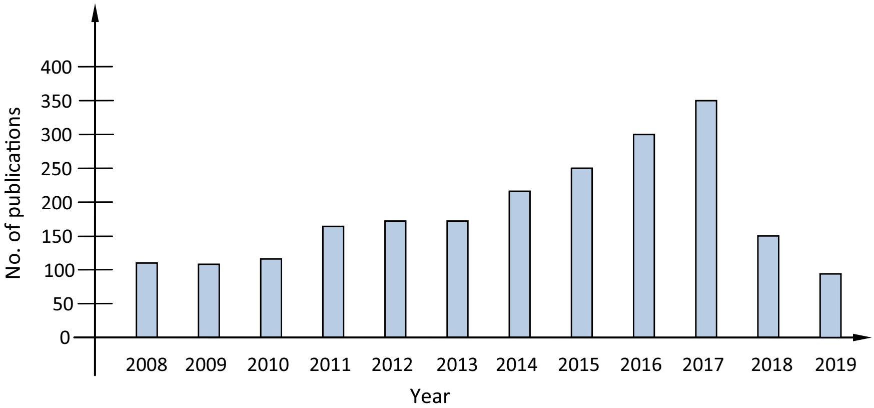


Fig. 19 Year-wise publication of 3D scanning. *Source* Scopus

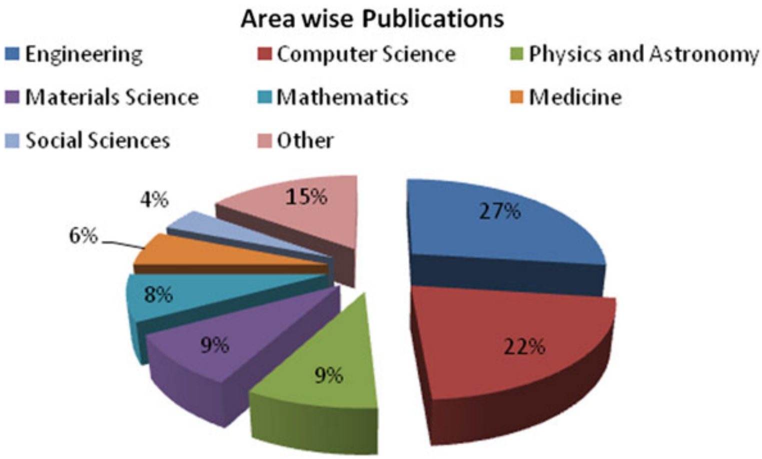


Fig. 20 Area-wise contributions of 3D scanning. *Source* Scopus

digitally acquiring the large structures like building exteriors or interiors and large site prospecting as well as mapping. It is difficult to compute the round trip time because of high light speed which leads to low accuracy that is near millimeters. The triangulation range finders are entirely converse to the time-of-flight range finders. These range finders have weakness for some constrained range of several meters, but equally have strength of higher level of accuracy near to tens of micrometers [30].

4.5 Comparison Table

See Table 1.

5 Application

The evolutions of non-contact scanning techniques would be useful in diverse applications. A few general examples which utilize one of the non-contact scanning techniques that are active and passive scanning techniques are cited and presented in Table 2.

6 Conclusion

The comprehensive study reveals that instead of threat by prodding of subject, the major concern is precision and accuracy for a three-dimensional scanning. In solution to this, contact scanner appears to be a suitable approach. On the other hand, non-contact scanners are best choice where subjects are affected by prodding and require high digital data acquisition speed. Further, non-contact scanner has been classified as active and passive three-dimensional scanners which functions for different surroundings and with their own level of accuracy and precision.

While categorizing the active laser scanners, it was found that active laser scanners work on three different principles; direct time of flight(first), indirect time of flight(second), triangulation(third). Where the first principle is suitable for very long range scans, the second principle is found to be suitable for short range scans while very short range scans are possible by third principle. The precision and accuracy of the above active laser scanners was found to be decreasing with increase in the ranges of laser scanners. Besides this, they also need enough time to digitally acquire the subject. Later for improved accuracy and fast time response, the structured light scanners were developed using triangulation principle. But, these structured light scanners require large initial investment. In order to obtain low cost and high speed, photogrammetry technique can be used while compromising the precision and accuracy. This type of approach comes under passive scanning technique.

Therefore, the selection of appropriate scanning instrument according to the application plays an important role to generate the accurate replica of the subject. The reported work will be helpful for suggesting the best scanning system for performing the chore of three-dimensional scanning.

Table 1 Evaluation of numerous three-dimensional scanning techniques

Sr. No	Scanning system	Time required	Cost	Accuracy	Usage
1	Contact technique	▲	▲	▲	Shiny, mirroring or transparent objects
2	Time of flight	▲	▼	■	Streetscapes, highways, buildings
3	Laser triangulation	▲	▼	▲	Replica production of small objects
4	Structured light (Triangulation)	▼	▲	▲	Reverse engineering
5	Photogrammetry	▼	▼	▼	Planimetric mapping, topographic mapping

Note Respective symbol represents the status.
▲ High ■ Medium ▼ Low

Table 2 General examples utilizing active and passive techniques

Technique	Scanning System	Application(s)		Citation(s)
Non-Contact Active Scanning	Laser Scanning	Heritage Monitoring	Statues of Michelangelo	[31]
			The Guyue Bridge	[32]
		Mining		[33, 34]
		Configuration Modeling for a Constrained Elastica Cable		[35]
	Mobile Laser Scanning	Extracting Road Information	3D Local Feature BKD	[36]
			Semiautomated Delineation	[37]
			Detecting Road Boundaries	[38]
		Street Object Recognition	Feature Matching	[39]
			Detecting Street Lighting Poles	[40]
	Terrestrial Laser Scanning	Archaeological Site Documentation	Byzantine Land Walls of Istanbul	[41]
			The Temple of the Sacred Tooth Relic at Kandy, Sri Lanka	[42]
			Geoarchaeological Sites in Jordan, Egypt and Spain	[43]
		Data Acquisition for Indoor Assets		[44]
		Urban Environment Modeling		[45]
	Airborne Laser Scanning	Landslide Activity Analysis		[26, 46]
		Forest Canopy Analysis	Quantification	[47]
			Estimating the LAI	[48]
	Time of flight, Structured Light and Phase Comparison	Motion Compensation		[49]
		A Tool-free Calibration Method		[50]
		Improved Coverage through Online Structured Light Calibration		[51]

(continued)

Table 2 (continued)

Technique	Scanning System	Application(s)		Citation(s)
		3D Shape Scanning with TOF Sensors		[52]
		Low-cost Hand-held 3D Scanning of Architectural Elements		[53]
		The Kinect Sensor	Objects	[54, 55]
			Persons	[56]
		Polarization and Phase shifting	Translucent Objects	[57]
			A Wideband Antenna	[58]
		An Infrared System for Metallic Surfaces		[59]
Non-Contact Passive Scanning	Photogrammetry	Fast Implementation of a Radial Symmetry Measure		[60, 61]
		Survey of Natural Areas of Special Protection		[62]
		Relative Pose Measurement of Satellite and Rocket		[63–65]
	Close-Range Photogrammetry	Automatic Camera Calibration		[41, 66, 67]
		Line Detection and Matching		[68]
		Forest Analysis	Plant Diversity and Surface Fuel Structure	[69]
			Mapping Eroded Areas on Mountain Grassland	[70]
		A Simulation Tool for the SRT		[71]
		River Surface Water Topography Mapping at Sub-mm Resolution and Precision		[72]
		City Modeling		[73]
	Aerial Photogrammetry	The ISPRS Benchmark		[74–76]
		Feature Extraction and Matching		[77, 78]
		Accurate Optical Target Pose Determination		[79]
		Survey of Historical Heritage	Pre-Hispanic Wall Painting	[80]

(continued)

Table 2 (continued)

Technique	Scanning System	Application(s)		Citation(s)
			Historical Buildings of the City of Strasbourg	[81]
		Street-level Modeling	Steep Surfaces	[82]
			Building Abstraction	[83]
			Effects of Image Orientation and Ground Control Point Distributions	[84]
		Topographic Monitoring		[85–87]
		Determining Fault Planes		[88, 89]
		Improving Height Accuracy Using a Multi-class System		[90]
	Terrestrial Photogrammetry	Coastal Projectors		[91]
		Landslides		[92]

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