A survey of Laser Range Finding

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Abstract

This report provides a informal survey of laser distance measurement. Applications of laser range finding are briefly discussed and various techniques for laser ranging such as active laser triangulation, pulsed time-of-flight (TOF), phase shift, FMCW, and correlation are described.

1 Introduction

Laser Range Finding has become an important method for distance measurements recently. Laser Range Finders (LRF) are being increasingly used for rapid 3D digitization. The process consists of scanning a physical object by a laser scanner which gives information about the geometry of the object and results in a 3D 'fingerprint' of the object. Combined with digital photos of the object that provide color and texture information, the 3D model can be used in virtual environments, special effects for the film industry, video gaming, and can also be used to create replicas i.e. rapid manufacturing and prototyping. Today commercial scanners are available that provide up to 25000 scan points per second with less than 1mm accuracy and that can operate to distances up to 20m and at the same time meet laser safety requirements. Some examples of 3D digitization are given below:

- LRFs can be used to rapidly acquire the geometry of building façades in a city. Combined with video images they can be used to create 3D photorealistic city models e.g. see `http://www-video.eecs.berkeley.edu/~frueh/3d/index.html`. In this work two 2D LMS SICK laser scanners, `http://www.sickusa.com`, are used to acquire the geometry of the building façades.

- LRFs are used to digitize precious works of art such as the works of Michelangelo, `http://graphics.stanford.edu/projects/mich/`, and the Statue of Liberty, `http://www.geomagic.com/advantage/graphics/liberty-index.php3`. This is being done not just for fun. Could the Statue of Liberty be rebuilt if damaged or destroyed? After the World Trade Center attacks, the value and vulnerability of U.S. national monuments are being given new consideration. And though there are numerous photos of Lady Liberty, there are no detailed architectural drawings that would enable an exact replica to be created. In the Digital Michelangelo project researchers used a custom built 3D scanner manufactured by Cyberware, `http://www.cyberware.com`. For the digitization of the Statue of Liberty a Cyrax 2500 3D scanner has been used, `http://www.neigps.com/products_cy_2500.php`.

- LRFs mounted on an airplane are used for example by U.S. Geographical Survey to build Digital Elevation Models and Digital Terrain Maps. In this context the process is also known as LiDAR and stands for Light Detection and Ranging. See `http://edc.usgs.gov/geodata/`.

- LRFs are used by entertainment studios to digitize humans for use in films, video games, special effects etc.

Besides 3D digitization of objects, LRFs can be used as sensors for robotic navigation, obstacle and collision avoidance, inspection etc.

The basic principle of active noncontact range finding devices is to project a signal (radio, ultrasonic or optical) onto an object and to process the reflected or scattered signal to determine the distance. The use of lasers in this context over other forms of signals is because of following reasons:

- It is easy to build compact systems that can produce highly focussed, low divergence beams. Radio and ultrasonic waves cannot be focussed adequately.

- A laser beam is bright and because of low divergence stays bright for large distances.

- Monochromaticity of the laser beam generally leads to simpler signal processing architectures.

In the following sections we describe various methods for laser range finding such as active triangulation, pulsed TOF, phase shift, FMCW (Frequency Modulated Continuous Wave), and correlation. In all these methods the light projection is most commonly done via a laser diode and associated optics such

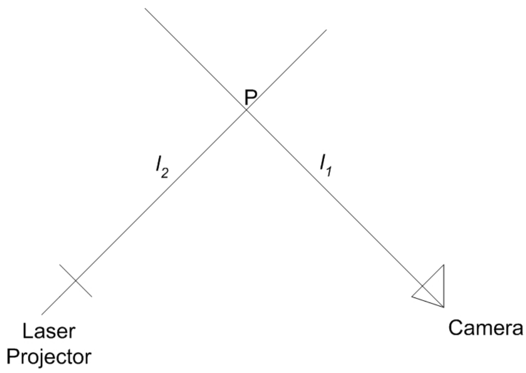

Figure 1: Principle of active triangulation. A laser projector projects a laser beam into the scene. The scene is imaged from another viewpoint by a camera. By intersecting lines l_1 and l_2 the 3D coordinates of P can be determined

as beam splitters and lenses etc. The laser diode converts electrical current into light wave or pulse. The reflected signal is detected with an avalanche photodiode (APD) and associated optics such as lenses for focussing the reflected signal. The APD converts light wave or pulse into electrical current. Amplifiers are used to suitably amplify the signal and appropriate signal processing electronics such as filters are used to reject noise, shape the signal, perform calculations etc.

2 Active Triangulation

In this method we have a laser projector projecting a laser beam into the scene and a camera viewing the scene as shown in Figure 1. Both the camera and the projector have a local $\hat{x}, \hat{y}, \hat{z}$ coordinate system associated with them. The distance between the camera and the projector is termed the baseline. The laser beam hits the 3D point P on an object and is scattered. The camera image of P is denoted by p. If we know the type of projection the camera uses (perspective projection being most common), the intrinsic camera calibration matrix [MSKS03] that takes care of parameters such as focal length of the camera, and metric size of pixels, and the 3D coordinates of the center of projection (COP) of the camera, then given p we know that P can only lie on a line l_1 as shown in Figure 1. If we also know the laser beam projection line relative to the local projector coordinate system and the 6 DOF (degrees of freedom) transformation between the projector and the camera then we can figure out the laser beam projection line l_2 relative to the camera coordinate system. By intersecting l_1 and l_2 it is possible to determine the 3D coordinates of point P. To recap following parameters must be known and are determined in a calibration step:

- Intrinsic camera calibration matrix.
- 6 DOF transformation between the projector and the camera.
- Projection line relative to laser projector coordinate system. This is analogous to the intrinsic camera calibration matrix.

To get an accurate estimate of P its pixel coordinates in the camera image i.e. p must be known precisely. It can be shown that the wider the baseline the less effect errors in pixel coordinates have on the estimate of P. However, the baseline cannot be made very large because then the laser projector and the camera would have lesser overlapping field of view (FOV) and the laser spot may not be captured in the camera image at all.

In practice the active triangulation method was invented to solve the notorious *correspondence problem*. The correspondence problem can be stated as follows: We are given two images I_1 and I_2 of a scene captured from two different viewpoints. Let a 3D point P have pixel coordinates p in image 1. We only know the value of p; the 3D coords of P, the intrinsic camera calibration matrix, and the 6 DOF transformation between the two camera viewpoints are unknown. Find the image coords of P in image 2. Thus the correspondence problem consists of establishing which point in one image corresponds to which point in another; in the sense of being image of same point in space. The active triangulation method using laser light solves the problem trivially by marking the 3D point P with the color of the laser light so that it can be easily matched between the two images. An undesirable side effect is that the true color at pixel p is lost — this phenomenon of missing color value is referred to as a hole in the image. Holes the size of a pixel can be easily filled by interpolating the color of surrounding pixels.

In order to find depth at multiple points in the scene, one solution is to sweep the laser beam with rotating mirrors. If this is done, note carefully that the camera and the laser projector have to be temporally synchronized with each other. It is difficult to get digital cameras that are relatively inexpensive and have frame rates greater than 30 Hz. Also to take an example of a 1024×768 pixel camera each 24 bit color frame represents 2.25 MB of data and frame rate of 30 Hz means data rate of 67.5 MB/s. This data stream has to be captured in real time on the hard disk of a computer.

In its simplest form the active triangulation method gives one depth value per image i.e. 30 depth points per second if we use a camera with a 30 Hz frame rate. This is an extremely low rate, especially considering the amount of image data that is being captured, if we want to reconstruct a range map of the whole scene. There are various modifications of the technique such as projecting multiple points, lines, structured stripes and patterns, temporal coding, spatial coding, using IR projector and camera to get away with the problem of holes etc. giving rise to a plethora of new issues. We will no longer pursue them here.

The projected beam has to be strong enough so that the laser spot is visible in the camera image and at the same time meet safety requirements. Recalling the beam waist formula for Gaussian Beams:

$$w(z) = w_0\sqrt{1 + (z/z_R)^2}$$

where

$$z_R = \pi w_0^2/\lambda$$

Thus, lower wavelength gives better depth of view (less divergence). Also in [BR91] the authors show that because of the coherent nature of laser projection, the imaged laser spot on the photodetector is corrupted with speckle noise and if σ^2 denotes the position variance which reflects the uncertainty in position of imaged laser spot then $\sigma^2 \propto \lambda^2$. Besides λ, σ^2 depends on the geometry of the optical system.

Yet another issue is that if a red laser light is being used it will not reflect off, e.g., blue surfaces. Transparent objects such as glass also do not give off any reflection of laser light.

3 Laser Pulse Time-Of-Flight Distance Measurement

The principle here is simple. A laser pulse is projected in the scene and the time the pulse takes to hit the target, reflect and reach the detector is measured. If d is the distance to the target, t is the echo time, and c is the speed of light, then

$$2d = ct$$

Note that for a non-ambiguous measurement t should be greater than the pulse width T_p. Thus

$$t > T_p$$

or,

$$d > \frac{1}{2}cT_p \tag{1}$$

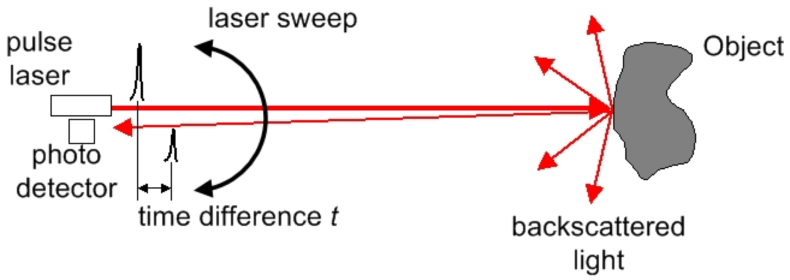

Figure 2: A 2D TOF LRF. The LRF is rotated about an axis perpendicular to the plane of the paper so that the beam sweeps the plane of paper as indicated by the curved arrows.

To plug in some numbers let $T_p = 10\text{ps}$. This gives $d > 1.5\text{mm}$. Practically, all the effort in designing a TOF LRF lies in measuring the echo time t accurately. The error in distance estimation is directly proportional to t.

$$\delta d = \frac{1}{2} c \delta t \tag{2}$$

An error of 1ps gives $\delta d = 0.15\text{mm}$.

TOF LRFs are the most commonly used systems for 3D digitization. They are usually available as 2D or 3D scanners. The schematic of a 2D scanner is shown in Figure 2. The laser beam is swept by a rotating mirror as indicated by the arrows in the figure. In this way a 2D scanner is able to provide scan points that lie in the plane in which the laser beam is swept. A good representative of current technology is the LMS scanner available from SICK, `http://www.sick.com`. The data sheet is shown in Table 1. From the data sheet it is seen that the scanner does a 180 degree sweep of the beam with 1 degree angular resolution every 13ms. This gives a scan rate of approximately 13846 points per second.

If the scanning plane is rotated at regular time intervals about the dotted axis indicated in Figure 3 a 3D scanner is obtained. A good representative is the DeltaSphere-3000 3D Digitizer from 3rdTech, `http://www.3rdtech.com`. Selected parameters from the data sheet are shown in Table 2.

The time discriminator is a very important part of the precision time measurement system in the TOF LRF. The task of the discriminator is to observe time information from the electric pulse of the detector preamplifier and to produce a triggering signal at the right instant. The choice of time derivation method depends on the desired time resolution, counting rate and required dynamic range of the pulse. Commonly used principles in discriminator design include leading edge timing (constant amplitude), zero crossing

Technical Data	LMS 200 ID	LMS 220 ID	LMS 211 OD
Range(max./10% reflectivity)	80m/10m	80m/10m	80m/30m
Scanning Angle	max. 180°	max. 180°	max. 100°
Angular Resolution	0.25°/0.5°/1° adjustable	0.25°/0.5°/1° adjustable	0.25°/0.5°/1° adjustable
Response Time	53ms / 26ms / 13ms	53ms / 26ms / 13ms	53ms / 26ms / 13ms
Resolution / systematic error	10mm / typ. ±15mm	10mm / typ. ±15mm	10mm / typ. ±15mm
Data Interface	RS 232 / RS 422	RS 232 / RS 422	RS 232 / RS 422
Switching Outputs	3×PNP; typ. 24 V DC	3×PNP; typ. 24 V DC	3×PNP; typ. 24 V DC
Laser protection class	1 (eye-safe)	1 (eye-safe)	1 (eye-safe)
Operating ambient temperature	$0 \ldots +50°$C	$-30 \ldots +50°$C	$-30 \ldots +50°$C
Enclosure Rating	IP 65	IP 67	IP 67 / heated front window
Dimensions (W×H×D)	$155 \times 210 \times 156$mm^3	$352 \times 266 \times 229$mm^3	$352 \times 266 \times 236$mm^3

Table 1: Data Sheet of LMS SICK scanner from http://www.sick.com

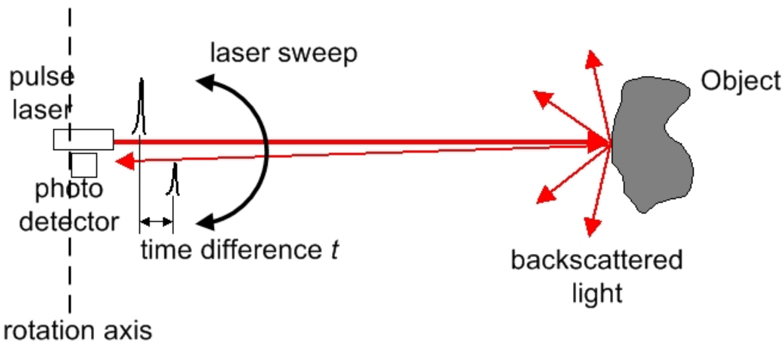

Figure 3: A 3D TOF LRF. This is formed by rotating the 2D LRF about the dotted axis shown in the figure.

Range	0.3m - 12m
Range Resolution	0.25mm
Range Accuracy	7.62mm at 12m
Angular Accuracy	0.015 degrees
Beam Diameter	2.54mm at 0m; 7.11mm at 9.1m
Scan Rate	25000 samples/second
Scan density	4-20 samples/degree, 1440-7200 samples/revolution
Field of View	$-60°$ to $+90°$ elevation, 360° azimuth
Power Requirement	12V DC, 3A (typical)
Operating Temperature	$0 - 45°$C
Dimensions	0.356m×0.356m×0.102m
Weight	10kg.

Table 2: Data Sheet of DeltaSphere 3000 3D Digitizer from http://www.3rdtech.com

timing (derivation), first moment timing (integration), and constant fraction timing. Constant Fraction Discriminator (CFD) is more popular. The principle behind the operation of CFD is the search for an instant in the pulse when its height bears a constant ratio to pulse amplitude. The occurence of this point produces a triggering pulse. The time interval between the start and stop pulses is measured with the time-to-digital converter (TDC), which is a fast, accurate and stable time-interval measuring device that uses e.g., a digital counting technique together with an analog or digital interpolation method [RRRK98].

[ABL+01] discusses major sources of error in a TOF LRF which are timing jitter and walk, nonlinearity and drift.

4 Phase Shift Distance Measurement

In this case a sinusoid signal is projected instead of a pulse and the distance to the target is estimated from the phase shift of the reflected signal. Let the projected signal be

$$s_E(t) = \cos(\omega_0 t)$$

and the reflected signal be

$$s_R(t) = \alpha \cos(\omega_0 t + \phi_d + \phi_e)$$

where α is the attenuation the wave suffers due to scattering at the target and propagation through the atmosphere, ϕ_e is an electronic phase shift due to emission and reception delay at the modulation frequency i.e. it is the phase shift associated with noise and errors. ϕ_d is the phase shift due to propagation to the target and containing the distance information. The reflected signal s_R and the emitted signal s_E are mixed with a signal $s_L(t) = S_L \cos(\omega_L t + \phi_L)$. After mixing s_R and s_L we get

$$s_{mRL} = \frac{1}{2}\alpha S_L \cos[(\omega_0+\omega_L)t+(\phi_e+\phi_d+\phi_L)]+\frac{1}{2}\alpha S_L \cos[(\omega_0-\omega_L)t+(\phi_e+\phi_d-\phi_L)]$$

After mixing s_E and s_L we get:

$$s_{mEL} = \frac{1}{2}\alpha S_L \cos[(\omega_0 + \omega_L)t + \phi_L] + \frac{1}{2}\alpha S_L \cos[(\omega_0 - \omega_L)t - \phi_L]$$

After low pass filtering we get two signals, one containing the distance information called the ‘mes’ and one being a reference called ‘ref’:

$$\begin{aligned} y_{mes}(t) &= Y_{mes} \cos[\omega_I t + \phi_d + \phi_e - \phi_L] \\ y_{ref}(t) &= Y_{ref} \cos[\omega_I t - \phi_L] \end{aligned}$$

M	f_0 (MHz)	δd (mm)	d_{max} (m)
4	16	7.15	9.56
64	256	0.447	0.586

Table 3: Accuracy and no ambiguity range as function of modulation frequency

where $\omega_I = \omega_0 - \omega_L$. The phase shift between y_{mes} and y_{ref} is $\Delta\phi = \phi_d + \phi_e$ If the distance to the target is d then

$$\begin{aligned} \Delta\phi &= \phi_d + \phi_e \\ 2\pi f_I \tau_m &= 2\pi f_0 \frac{2d}{c} + \phi_e \\ \tau_m &= \frac{f_0}{f_I}\tau_p + \tau_e \end{aligned} \tag{3}$$

τ_e has to be measured by a calibration process. The phase shift method in essence measures τ_m and estimates the propagation delay τ_p indirectly via equation (3). Since τ_m is greater than τ_p by a factor of approximately f_0/f_I, it is easier to measure τ_m accurately. The time interval τ_m may be obtained by direct counting at a frequency f_c. The resolution of the system is then 1 period of this counting signal so

$$\delta d = \frac{1}{2} c \delta\tau_p \simeq \frac{1}{2} c \frac{f_I}{f_0} \delta\tau_m = \frac{c f_I}{2 f_0 f_c} \tag{4}$$

All the frequencies can be synthesized from a reference clock operating at f_{CLK}. Let $f_0 = M f_{CLK}$, $f_I = f_{CLK}/P$, $f_c = N F_{CLK}$. Then

$$\delta d = \frac{c}{2NPM f_{CLK}}$$

Because of the 2π ambiguity in phase shift of two sinusoids, ϕ_d must be less than 2π for a non-ambiguous distance measurement. This gives

$$\text{No ambiguity range: } d < \frac{1}{2}\frac{c}{f_0} \tag{5}$$

To plug in some numbers let $f_{CLK} = 4$ MHz, $N = 41$ and $P = 32$ so that $f_I = 125$ kHz and $f_c = 164$ MHz. In table 3 two values of M and corresponding accuracy and no ambiguity range are given.

Both δd and $d_{\max}$ are inversely proportional to f_0 from equations (4) and (5) respectively. Thus a high modulation frequency gives better accuracy in

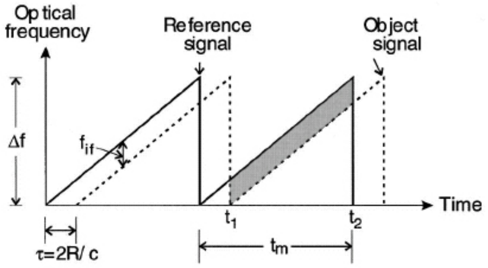

Figure 4: Principle of FMCW. Incident and reflected signals have a frequency profile as shown in the figure and are time shifted. Source [ABL+01]

range measurement but it also decreases the no ambiguity range. A solution is to work with a twofold modulation frequency in which the target is localized at low f_0 and then accurate measurement is performed at high f_0.

A good discussion on the phase shift method can be found in [PJ01].

5 Frequency Modulated Continuous Wave

In the phase shift method we detected the phase difference between incident and reflected sinusoids. In the FMCW method we detect the frequency difference. The interest in the FMCW technique is due to the large dynamic range and the high resolution, particularly at short range sensing.

The FMCW method projects an optical signal whose frequency varies with time as shown in Figure 4. The periodic and linear frequency chirp may practically be performed by applying a saw-tooth bias current to the modulator section of a wavelength tunable laser diode. The reflected signal has the same frequency profile shifted by the propagation time as shown by the dotted lines in Figure 4. The emitted and reflected signals are mixed in a square law detector diode whose main ac output is at the frequency difference f_{if} of the two optical signals. The detector output is fed into an amplifier-limiter so that unintentional amplitude modulation is suppressed. Finally, the intermediate frequency f_{if} is measured with a frequency counter. From similar triangles in Figure 4

$$\frac{f_{if}}{\tau} = \frac{\Delta f}{t_m}$$

$$\tau = \frac{2R}{c} = \frac{f_{if} t_m}{\Delta f}$$

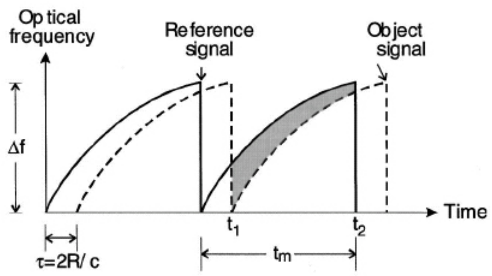

Figure 5: Problems with FMCW. In practice a ramp like frequency profile is not easy to obtain. Source [ABL+01]

$$R = \frac{f_{if}}{2\Delta f} c t_m$$

In this way R can be estimated from a measurement of f_{if}. Thus in FMCW the distance sensing is done by an electric frequency measurement (usually in the kilohertz regime). The ramp period t_m is of the order of 0.1 to 1 ms. Since the ramp period can be chosen arbitrarily, the FMCW method can determine τ values in the picosecond range, corresponding to millimeter distances R, by simply performing a frequency measurement in the kilohertz regime. Consequently, no high-speed electronic is required to determine delay times even in the subpicosecond range, corresponding to micrometer distances R, e.g., in the automated inspection of printed boards.

The main issue in FMCW is that the frequency modulation response of a laser diode is, in general, nonuniform against the modulation frequency, so that a linear optical frequency sweep cannot be realized by a linear modulation of the control current. In addition, the frequency versus control current characteristic is also in general nonlinear. As a consequence, deviations from the linear ramp as shown in Figure 5 usually occur. While the total phase difference ϕ as indicated by the shaded areas in Figures 4 and 5 is still proportional to τ and the distance R as long as $\tau \ll t_m$, the variation of f_{if} during each ramp increases the total intermediate frequency bandwidth and, consequently, the noise level that finally limits the accuracy. For further discussion see [ABL+01].

6 Correlation Method

In order to overcome the linearity problem mentioned previously with FMCW, a solution could be to determine the 'resemblance' between the emitted signal and the received signal. That means to determine the correlation between the emitted and received signals [JL00]. This resemblance reaches its maximum value at the moment corresponding to the duration of the propagation delay of the laser beam. Thus it is important to notice that with such a method, the advantage of phase shift or frequency difference measurement compared to TOF pulse measurement is in a sense lost because we are directly measuring the TOF. Thus this is really a TOF technique with yet another way to estimate the TOF. It is necessary to take into account the addition of noise to the emitted and the received signals and the possibility to have coupling phenomena between emitted and received signals.

Let the emitted signal be denoted by $s_E(t)$ and the received signal be denoted by $s_R(t)$. For digital correlation the signals are sampled at a sampling rate given by f_{SP} which is of the order of 1GHz. If we take N_p samples for correlation then the correlation function is given by

$$C(nT_{SP}) = \frac{1}{N_p} \sum_{k=0}^{N_p-1} s_E(kT_{SP}) s_R((k-n)T_{SP}) \tag{6}$$

where $T_{SP} = 1/f_{SP}$ is the sampling period. If C reaches its maxima at $n = M$ then the TOF is estimated as MT_{SP} (without any interpolation). Calculation of range is straightforward.

The number N_p of points used for correlation influences the measurement on several criteria. The first criterion is the quality of the result obtained when computing the correlation; the longer the signal, the higher its energy, and more optimized is the computing of the correlation. The second criterion is the maximum distance that can be measured. A good compromise is $N_p = 10^4$, which gives a satisfying result on the first criterion and enables distances up to 1km [Jou02].

The robustness of such a method to the addition of non-correlated noise to the emitted and received signals is one of its main advantages. The capacity of the correlation to extract useful information while signal level is below the noise level has been successfully used with the GPS (Global Positioning System) [HWLC92]. Finally, whereas the coupling between emitted and received signals has a distorting influence on the phase shift LRF, it is much less of a problem with the correlation LRF. A coupling produces a correlation component near the origin. A simple software processing makes it possible not to take this component into account, but it is necessary to test if the coupling does not saturate the reception stage.

7 Conclusion

We presented a broad survey of laser range finding. Applications of LRFs were briefly discussed and following methods of laser ranging were described: Active Triangulation, Time of flight, phase shift, FMCW, and correlation. Salient features of these methods were noted and limitations were mentioned. One important technique that has not been covered is interferometry. See [DSZ98] for a discussion of interferometry applied to laser ranging. The interferometric method is used to provide high resolution distance estimates over short distances such as 200mm range measurements with 10μm accuracy. Its use mainly lies in research labs and commercial applications are yet to be seen.

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