Optical three-dimensional sensing for machine vision

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Abstract. A review of optical range sensing techniques for machine vision is given. Four basic categories of range sensing techniques are discussed: geometric techniques, time-of-flight techniques, interferometric techniques, and diffraction techniques. The basic principles are elucidated, and general comparisons are made between the groups. Representative examples are given of many different approaches. The challenge for optics and optical computing is to develop new range sensors that are fast and accurate and require little or no post-detection processing.

Subject terms: optical computing; machine vision; optical sensing; range sensing.

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1. INTRODUCTION
The modern-day computer and digital electronics are fraternal twins, both born from the same seed of invention. Since their conception, their destinies have been firmly interlocked. In recent years optical computing techniques have demonstrated several distinct advantages over conventional electronic techniques in certain computing applications. In order to gain an inroad into the domain of electronic computing systems, optical techniques must offer truly dramatic advantages, and they must interface with electronic systems in a totally transparent way. As the new challenger, all the demands are placed on the optical systems to prove their worth.

Given the monumental task of breaking into a field totally dominated by an established technology, one might look for an area in which optics is already established and attempt to introduce optical computing there. One example is image sensors, where optics is firmly entrenched. It is also an area that is receiving considerable attention currently because of its role in machine vision. Although image sensing and more general 2-D optical sensing techniques are well developed, the requirements of machine vision systems have made sensor development an important research area.

Although there are many aspects of sensor development, a fundamental problem for vision systems will always remain: how to obtain more useful information in less time. The time constraint manifests itself in one of the two possible ways. On one hand, the physical detection process may be the limiting factor in the measurement time. However, in many instances, the desired information is not obtained directly but is only extracted through post-detection processing. In such instances, the required post-processing is often the limiting factor.

Thus, there are two directions one can follow to improve the effective throughput of optical sensors. The first is to improve the physical sensors or the measurement technique in order to reduce the measurement time. The second direction is to introduce new measurement techniques that eliminate or reduce the required post-processing either by performing the processing optically or by changing the technique in such a way that the desired information is obtained directly.

Before going into a discussion of specific machine vision techniques, we should consider briefly what kind of information we are interested in and what kind of information we can easily obtain.

The primary information to be sought with vision systems is spatial information. Spatial information can be further subdivided into three categories: position, orientation, and shape. Position information is important in assembly or part-acquisition applications where one must determine part locations. Orientation is also important in acquisition problems. Shape information is important in object recognition, in part acquisition, and in inspection. Position information can be associated with a single point. It involves three degrees of freedom and thus requires at least three measurements. Orientation can also be defined as a point property. It, too, has three degrees of freedom associated with it and requires at least three measurements. However, if one wishes to determine orientation from position measurements alone, it takes at least three position readings (i.e., nine measurements) to determine a plane, and thus a surface orientation. Finally, shape information has many degrees of freedom, depending upon the complexity of the surface. In general, one needs at least relative position information for all points on a grid covering the surface.

A second type of information to be acquired by many machine vision systems is reflectance or transmittance, generally as a function of position. This information can be monochrome information, or it can be acquired for several different colors or wavelengths. In the former case, it represents one additional degree of freedom per point, whereas in the latter case several degrees of freedom may be involved.

Although one might add other features to the above list, the
information most often used either is one of the above or is obtainable from them.

Which of these parameters can we easily obtain? Imaging sensors provide us with intensity as a function of two spatial variables. The spatial variables are those perpendicular to the line of sight. We can obtain extra degrees of freedom by taking measurements as a function of time, wavelength, or polarization. Thus, we see that the normal detection scheme provides us with all but one of the generally desired variables: the longitudinal position variable \( z \). We will refer to this as range information. Since the other variables are obtainable in a straightforward manner, we will concentrate on means of acquiring the range variable \( z \). Since \( z \) is not directly measurable, the \( z \) information will have to be encoded in one of the measured variables. Thus, there will always be a trade-off in \( z \) resolution versus resolution in one or more of the measured variables. In the following sections, we discuss various range measurement techniques in generic terms. The techniques are divided into four basic categories: geometric, time-of-flight, interferometric, and diffraction techniques. For each category, the basic principles are discussed along with the measurement trade-offs, and examples are given. We emphasize the commonality of many different techniques with the thought that systems based on the same fundamental principles will have many common characteristics and many common strengths and weaknesses. This review is not intended to be an exhaustive review of the various specific implementations of range measurement techniques. Rather, our intention is to provide a framework for understanding and comparing range measurement techniques and to supply some representative examples. A recent review of specific range measurement techniques was given by Jarvis.1

2. GEOMETRIC RANGE MEASUREMENT TECHNIQUES

The largest and most common class of range measurement techniques is that based on geometric measurements. This is a generalization of the triangulation concept. Triangulation is certainly the range measurement technique with the longest history. It is an important factor in the human visual system and was probably the first scientifically applied range measurement technique. It was, for example, used by Egyptians in construction of pyramids.

The basic principle in triangulation is shown in Fig. 1. The measurement system establishes a pair of similar triangles, one between the object and the measurement fulcrum, and one between the object and the measurement fulcrum. The baseline \( b \) of the object triangle is assumed known, as is the height \( h \) of the image triangle. The base \( \Delta x \) of the image triangle is measured. From this, the height or range \( z \) of the object triangle is determined. The measurement equation is

\[
\frac{\Delta z}{\Delta x} = \frac{b}{h}
\]

where \( \Delta x \) is the measured parameter. This is shown in Fig. 2. Several observations can be made about this equation. First, since \( h \) (and usually \( b \)) is under our control, this technique can be easily scaled over a wide range of \( z \) values. Second, there is a monotonic relationship between the range and the measured variable \( \Delta x \). Thus, in principle, the technique is useful for all values of \( z \). The measurement range is limited only by the detection system. Finally, the nonlinear relationship between \( z \) and \( \Delta x \) implies that uniform steps in \( \Delta x \) yield nonuniform steps in \( z \). In general, the accuracy will be nonuniform with the best accuracy for small \( z \) values. For a detection system with a fixed space-bandwidth product, there is a direct trade-off between the number of object points \( P \) that can be measured in one cycle and the number of range resolution elements \( R \) available. The detector space-bandwidth product \( S \) is in general equal to the product of \( P \) and \( R \).

There are numerous techniques that we classify under geometric techniques. These techniques share the common measurement principle discussed above. Most of the techniques in use today are active systems that illuminate the object in an advantageous manner. We refer to these as structured illumination methods. There are also many passive techniques that do not rely on special object illumination. We will discuss these two classes of techniques separately.

2.1. Active techniques

Of the active, structured illumination approaches, the simplest is the projection of a single point onto the object and the subsequent imaging of this point on a detector. The displacement of the image point relative to a known reference point gives the distance to the object. The projected point is scanned across the object to provide range data over the entire object field. Kanade developed a system of this type that uses a scanned laser beam and a single-element position sensing detector, as shown in Fig. 3. Here the image point coordinates are provided by the position sensing detector, and the reference point is determined by the computer from the scanning coordinates. Parthasarathy et al. describe a similar system with a linear array detector.

This technique can be easily extended for line-by-line data acquisition, as opposed to point-by-point detection, by projecting a line or sheet of light and using a two-dimensional detector. The image of each point on the projected line of light will be displaced in a direction orthogonal to the line by an amount related to the range.
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Fig. 3. Point projection range measurement system (after Kanade).

Fig. 4. Light stripe technique. The distortion of the image of a straight line projected onto a 3-D scene provides range information.

Fig. 5. Consight light stripe projection system (after Holland et al.).

Fig. 6. Grid projection technique (after Will and Pennington).

Fig. 7. Coded grid projection (after Altschuler). Projecting a series of binary grid patterns on the object encodes the range to any point on the object.

...for the point (see Fig. 4). Several systems have been developed using this principle, including the Consight system developed and used at General Motors (see Fig. 5) and some commercially available systems.*

This approach can be even further extended by projecting a grid plane on the object, as discussed by Will and Pennington* and as shown in Fig. 6. Although this increases the potential data acquisition rate, it introduces a range ambiguity factor since one cannot uniquely identify a particular projected line in the image. By imposing constraints on the measurement system, the potential ambiguities can be avoided or resolved. Grid coding has also appeared in many different forms. Altschuler et al. have developed a form of grid coding that minimizes the number of measurements required to obtain a given number of range resolution elements.† Their concept is depicted in Fig. 7. The object is illuminated by a series of grid patterns produced by the series of shutters. This series
of illumination patterns uniquely codes each angular position. The detector also ascribes a specific angular coordinate to each object point. The intersection of the back projection of these two coordinates gives the 3-D location of the object point. Hence the series of images can be used to determine the range of each object point.

In triangulation systems, the key parameter is the displacement of an image point from a reference point in the detector plane. In all of the above systems, that reference point was a virtual point that was determined from the system geometry. A large body of work exists on an alternate approach to topographic measurement using moire techniques. In moire systems, the object is illuminated with a grid pattern as in grid coding, but then a second grid is placed in the measurement plane. This second grid in effect provides a physical set of reference points in the detector plane. What is actually monitored in moire systems is not the phase shift between the two gratings, but rather a beat frequency. This corresponds to rate of change of phase shift. For example, if a grating is projected on a surface from a given direction and then is viewed from a different direction, in general the apparent grating frequency will be different from the actual frequency in the grating. The apparent frequency at the object can be found by projecting the grating vector \( G_o \) onto the object surface and then projecting the resultant vector \( G_s \) onto a plane normal to the viewing direction (see Fig. 8). The moire grating vector \( G_m \) is the vector difference between the image grating vector \( G_i \) and the reference grating vector \( G_r \) as shown in Fig. 8. With such a system, one can determine the tilt of the object surface, given the projection and viewing geometries. Thus moire techniques generally provide different range rather than absolute range. The moire technique is particularly useful for visual analysis.

Normally the second grid in a moire system provides a set of uniformly spaced reference points that define a virtual reference plane. Yatagai and Idesawa have pointed out that by distorting the second grid in a predetermined fashion, the effective reference surface can be an arbitrary shape. Thus a system can be designed to produce a particular fringe pattern (e.g., something simple like linear fringes) only when a given object shape is present. This concept, which has been extended by Lohmann and Po-Shiang, should be particularly useful in inspection applications.

An alternative approach to triangulation is to have a system in which the baseline is defined at the object, as indicated in Fig. 1(b). This could be achieved, for example, by projecting two parallel points or lines of light onto the object and measuring their separation at the image plane. This has the advantage of reducing the sensitivity to the system geometry. Its main drawback is that it severely limits the length of the baseline. Although this technique has not been used in an active mode, a passive version has been proposed that will be discussed in the next section.

### 2.2. Passive techniques

Although the above techniques require special illumination, there are several geometric techniques that are passive, using ambient illumination. Passive techniques are much more flexible than the active techniques. However, the passive approaches generally place a large burden on post-detection processing of the data. The most obvious passive triangulation system is the comparison of stereo pairs, i.e., images taken from opposite ends of a known baseline. The main problem is locating matching points. One way of simplifying this task is to precede the matching algorithm by an edge detection algorithm to reduce the number of points involved. This is particularly useful for scenes of simple geometric objects. Another means of reducing the required computation is to use a hierarchical approach that first matches images at a very coarse resolution and then proceeds to matches at progressively finer resolution scales. This is particularly useful where global matches are desired but might ordinarily be difficult to obtain due to lighting or geometric distortion variations that change over the scene. Many other techniques have been developed along these lines, along with techniques using other geometric clues such as perspective, scaling, and shading. Since none of these involves special detection schemes, but rather, each emphasizes image understanding algorithm development, we will not discuss them here but refer the interested reader to the literature.

Sweeney and Hudelson have proposed a passive system that allows one to track the 3-D location of specific points on an object. The technique requires special target structures that mark the points of interest on the object. Sweeney used Fresnel zone plates as target patterns. Correlation techniques applied to the images of the targets provided 3-D information. The range information effectively comes from the scaled size of the images. This technique corresponds to that depicted in Fig. 1(b), where the fixed baseline is on the object.

It should be noted that many of the autotousc systems on cameras are geometrical range measurement systems. These systems provide moderate speed and range resolution with low spatial resolution in a relatively inexpensive package.

### 2.3. Summary of geometric techniques

Geometric techniques are the most widely used range measurement techniques. They offer several general advantages. They are conceptually simple and straightforward to implement. They can be scaled over a large range of measurement values. Their accuracy can also be scaled over a large range. One generic problem with triangulation techniques is measuring data. Since 3-D scenes are being viewed from at least two different perspectives, there generally will be points that are visible in only one of the views. Also, they are inherently point- or line-of-site systems so there are often speed limitations. Finally, since these are imaging systems, there are always depth-of-field considerations that, varying depending, limit the useful measurement range.

### 3. TIME-OF-FLIGHT RANGE MEASUREMENT TECHNIQUES

Time-of-flight (TOF) range measurement has a history almost as long as triangulation. It is apparently used in the vision systems of certain animals such as bats and dolphins. It has been a useful tool for humans since people started dropping rocks down deep holes or listened for the time delay between lightning and the associated thunder.

The principle of TOF measurement is quite simple. One has a signal carrier, such as acoustic or optical waves, that is assumed to travel with a known velocity. Typically, the carrier is sent from the measurement system, reflects off the object, and returns to the observer, who measures the total elapsed time. In order to get three-dimensional information, the signal beam must be scanned over the scene. In some instances, only one-way flight may be involved. A TOF system is depicted schematically in Fig. 9. Given the velocity of propagation \( v \) and the measured time-of-flight \( \Delta t \), the range \( z \) is given by

\[
z = \frac{v}{2} \Delta t.
\]

where \( v \) is a constant determined by the system geometry (see Fig. 10). Typically, the signal travels from the measurement system to the
3.2. Chirp techniques

The time-bandwidth product $TW$ of the transmitted signal in the single-pulse case is just 1. The signal-to-noise ratio and thus the measurement accuracy of the system can be improved by transmitting signals with a $TW$ larger than 1. This is the concept used in radar and sonar systems which typically transmit a chirp, a signal whose frequency varies linearly over the duration of the transmission. The chirp signal not only increases the SNR but also provides a convenient means of obtaining line-of-sight velocity via Doppler shift, as well as range information. The Polaroid ultrasonic ranging system uses a form of chirp transmission to obtain range information, albeit with very little lateral spatial resolution.

3.3. Summary of time-of-flight techniques

The primary advantages of TOF techniques compared to geometric techniques are the elimination of the missing points problem and the uniform sensitivity throughout the measurement range. The main problem with TOF systems is their lack of scalability; current implementations tend to be slow and have poor SNR, two interrelated problems. TOF techniques do not require imaging on the detection end. Thus, they do not have the same depth-of-field restrictions that triangulation systems often have. They do, however, still require projecting a small point of light onto the object if spatial resolution is desired. There are depth-of-field restrictions associated with this projection.

4. INTERFEROMETRIC TECHNIQUES

A third range measurement technique is interferometry. Although the phenomenon of interference apparently has not been exploited in biological sensory systems, it has manifested itself to people in the form of the colors often seen in thin films such as soap bubbles or oil films on water.

Interferometric measurements rely on the fact that waves have a certain fixed wavelength that can, in effect, be used as a measuring stick. Interferometric measurements involve a signal beam that is split into two components. One beam is sent to the object and reflected back. It is then compared with the second beam, which has traversed a known reference path. This beam serves the function of a local oscillator. The relative shift between these two beams is measured in terms of the wavelength. This is indicated schematically in Fig. 11. Given that the path length difference between the object and reference beam paths is $kz$, the detector will read an intensity $I$ given by

$$I = 1 + a \cos \left( \frac{2\pi z}{\lambda} \right),$$

where $\lambda$ is the wavelength of the illumination and $a$ (initially) is a constant. Inverting this, we get a measurement equation of the form

$$z = \frac{\lambda}{2\pi} \cos^{-1} \left( \frac{1 - I}{a} \right),$$

as shown in Fig. 12.
Comparing this with the previous measurement equations, we see several major differences. First, the measurement variable is the intensity $I$, rather than time $t$ or space $x$. On the one hand, this implies there is no trade-off in either spatial or temporal resolution involved in measuring range. On the other hand, our ability to resolve intensity levels is generally rather limited so that our range resolution will also be limited. Second, we note that the range is not uniquely determined by the intensity since there is not a monotonic relationship between the two. In fact, since the intensity $I$ is a periodic function of $z$, a single measurement is infinitely degenerate. The measurements are only unique over a range of $\lambda/2$ and are periodic with period $\lambda$. Because of this degeneracy, interferometry can only be used for obtaining absolute range measurements over finite ranges. Often it is used instead to obtain relative range measurements.

Another feature of the interferometric systems is that the fundamental scaling factor $\lambda$ is a property of the illumination. However, in contrast to the TOF systems, where scaling was fixed by the signal velocity, $\lambda$ can effectively be changed by using modulated illumination in interferometric systems. This is, however, a limited blessing since even with $100$ MHz modulation rates, the modulation wavelength will be on the order of $3$ m for optical waves. Thus, there is a tremendous gap between the micrometer wavelengths of unmodulated light and the longer wavelengths of modulated light. This gap unfortunately covers an important range. When using modulated beams, one can improve the phase measurement accuracy by using electronic phase-locking techniques. Then one can trade off temporal resolution for phase resolution, and thus for range resolution. Electronic techniques easily allow for phase measurements to $10^{-3}$ cycles or better. Thus, even with the long wavelengths associated with modulated beams, reasonable range accuracies can be obtained. At the other end of the spectrum, if micrometer accuracies are desired, extended relative range measurements can be made in this regime by fringe-counting techniques. Next we will briefly discuss unmodulated and modulated interferometer techniques.

### 4.1. Unmodulated techniques

Due to their very limited measurement range, simple, single-wavelength interferometers are only used in special applications such as lens testing where the submicrometer resolution is critical. The most direct means of extending the usable range is to utilize temporal fringe counting or spatial fringe analysis techniques to overcome the inherent ambiguity. In the former case, temporal resolution is traded for the extended range, while in the latter case the trade-off is in lateral spatial resolution.

The analysis of spatial fringe patterns, or interferograms, is a well-established process. It involves measuring the displacement of a fringe, and thus the underlying phase shift, as a function of position (see Fig. 13). Thus it is well-suited to obtaining the 3-D coordinates of a surface. There are many commercially available systems for analyzing interferograms. These systems are typically intended for measurement over relatively small ranges.

There is also a commercially available system that uses temporal fringe counting to measure distances to a fixed point at ranges up to 60 m with 0.01 $\mu$m resolution and 1 part in $10^4$ accuracy. This system monitors the distance to a given reference point as a function of time, as diagrammed in Fig 14. Of course, only relative position information is obtained. If the beam is ever interrupted, the distance reference is lost.

An alternate means of extending the useful measurement range is to employ multiple wavelengths. The output of an interferometer of a single wavelength is periodic as a function of path length difference. The period is equal to the wavelength. If measurements are made with two separate wavelengths, $\lambda_1$ and $\lambda_2$, the combined measurements are still periodic but the period $\lambda_p$ is

$$\lambda_p = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1}$$

If $\lambda_2 - \lambda_1$ is small, then $\lambda_p \gg \lambda_1$ or $\lambda_2$. Thus, the useful measurement range can be significantly increased, although it should be pointed

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*Hewlett-Packard Dimensional Measurement System, Models 5526A and 5526A*
4.2. Modulated techniques

By modulating the signal beam, it is possible to alter the effective wavelength of an interferometric system. The signal beam is modulated by an electronic system that also generates a local oscillator signal. The modulation of the signal beam reflected off the object is compared with the local oscillator. Again, we are making an interferometric phase difference measurement. The output signal is a periodic function of the object range. The period now, however, is equal to the modulation wavelength, which is under the experimenter's control. As mentioned earlier, these wavelengths are typically in the millimeter to centimeter range. Thus, high resolution range measurements require very high resolution phase measurement on the modulated signal returned from the object. This, in turn, requires time averaging over many periods of the modulation. Thus, there is a direct trade-off in range resolution and temporal resolution (see Fig. 15). Nitzan et al. describe a range-finding system based on this technique. A ranging system using three separate modulation frequencies is commercially available. This system is capable of measuring ranges from millimeters to kilometers. It can only measure distances to particular points, generally designated by a corner cube reflector, and takes a great deal of time to make a measurement.

It should be pointed out that many systems classified here as nonmodulated techniques actually use modulated signal beams (e.g., 526-N and 526-NA). The distinction is that in those cases the modulation is introduced as a carrier to enable the use of ac detection methods. In the modulated techniques described in this section, the modulation is used to define the measurement wavelength.

4.3 Summary of interferometric techniques

General interferometric measurement is relatively limited in its applications due to the degeneracy of the measurements. However, it is an extremely accurate tool. Commercial systems utilizing interferometric measurements have been developed for numerous applications, covering the distance scale from nanometers to kilometers. Some techniques are also being actively pursued for robotic applications where one wants to monitor the position of a small point very accurately.

5. DIFFRACTION RANGE MEASUREMENT TECHNIQUES

A recent trend in range measurement research has been to explore diffraction-based measurement techniques. Of all the phenomena described in this paper, diffraction of light was the last to come to man's attention, being first observed in the seventeenth century. Diffraction techniques were also the last to be considered for range measurement. The two techniques we will describe do not form a neat, unified group, as did the techniques in the previous sections. The only common thread is that they rely upon diffraction. The first diffraction technique is due to Jain. If a spot on an object is coherently illuminated, the scattered light will form a speckle pattern on a screen (see Fig. 16). The correlation length c of that speckle pattern depends upon the distance between the object and the screen, among other things. Thus, measuring the correlation length provides distance information.

This approach combines some of the best features of triangulation and time-of-flight techniques. It is easily scaled by changing the spot size and can be used over a very broad range of distances, as with triangulation. However, the signal is transmitted and received much like the TOF systems. Thus, there are no missing points, and no imaging is required on the detection end of the system.

The final range measurement system we will discuss is based on measuring the contrast of a periodic structure. When an object is coherently illuminated, it produces a diffraction pattern that varies in a well-known way as a function of the propagation distance. If the object is a grating, the diffraction pattern and the form of the variation are particularly simple; namely, the intensity of the diffraction pattern demonstrates a periodic modulation whose contrast (of the fundamental frequency) varies as a function of z. Thus, if a second object is illuminated through a grating, by measuring the modulation contrast on the object, the distance from the grating to the object can be determined (see Fig. 17). This system has the advantages that there are no missing points and there are no depth-of-field restrictions on the projection side of the system. However, the main advantage is the speed of the data acquisition. For previously discussed systems, kihertz data rates are difficult to obtain and the measurement process is generally much slower. With this approach, the entire field of interest is illuminated in parallel and viewed with a video.
camera. A simple analog filter is used to measure the fringe contrast on the video signal. Thus, megahertz data rates are achieved, allowing real-time range measurements for three-dimensional scenes.

The system is fundamentally limited by the fact that the contrast is actually a periodic function of z. Thus, the same sorts of ambiguities exist as were found in the interferometric systems. This limitation can be alleviated if necessary by various techniques, many of them analogous to those used in interferometry. Since the basic period is easily scaled by changing the grating in the system, it is often unnecessary to consider the ambiguity problem. Another limitation of this approach is its low accuracy, which is tied to its high speed and its spatial resolution. A final practical limitation is set by the laser power required for illuminating a three-dimensional scene. This problem also arises in other systems that use laser illumination and similarly limits their speed and accuracy (e.g., see Refs. 1 and 4 and Footnote 1).

In summary, diffraction techniques may offer some new approaches to range measurement that either combine the best features of previous techniques or provide a whole new measurement perspective. These techniques will often be limited by the power of the coherent sources they require.

6. MEASUREMENT EFFICIENCY

Since the stated goal for range measurement systems is to obtain more information in less time, it is important to see how efficient the measurement process is. Assume that the measurement system is set up so that each measurement is made at a fixed signal-to-noise ratio (SNR) that is just large enough to allow binary readings to be made with a predetermined reliability. Then the efficiency could be measured in terms of the number of useful bits of range data obtained per bit of measured data. Thus if one has to take many measurements to obtain a single bit of range data, the measurement process is inefficient. Given the fixed SNR, it is reasonable to assume that the number of measurements can be related directly to the total required measurement time. Thus an inefficient system is a slow system.

As an example, consider a triangulation system in which a single point is projected on the object and its displacement from a reference point is measured. The measurement process might consist of taking a linear array of N detectors and seeing which one is illuminated by the projected spot. Thus we measure N bits of data. However, we range resolution is N points, and thus we only obtain log₂N bits of range information. This is not an inherent problem of triangulation, however. This can be seen from the system of Altschuler, described previously. Here M bits are measured at each object point to obtain M bits of range information, an ideal situation from an efficiency standpoint.

Exactly the same considerations apply to time-of-flight measurements. Although none of the systems described has a very high efficiency, the Altschuler model can in principle be transfered to the TOF approach.

The interferometric approaches are somewhat harder to analyze, although it is clear that if fringe counting or fringe following is required, the efficiency may be very low. The diffraction techniques also tend to have low efficiencies since several spatial measurements have to be taken to obtain a range point. It is worth investigating more efficient implementations of these important techniques.

7. CONCLUSION

Four different classes of range measurement techniques have been discussed. By studying the fundamental concepts behind these techniques, insight can be gained into the generic strengths and weaknesses of the different approaches. Geometric techniques are the commonest, due mainly to their simplicity and flexibility. Time-of-flight techniques are somewhat limited by the fixed propagation velocity of optical or acoustic beams, but they avoid the missing points problem and do not require imaging of the object. Interferometric techniques have the problem of ambiguous readings. However, they can be extremely precise, and many commercial systems are available for certain applications. Diffraction techniques may offer new opportunities for range sensing systems, particularly for relatively small volumes. One important issue that remains is to develop efficient implementations of all these techniques to maximize the number of measurements, and thus the time, required to obtain the desired range information. In all, there are many opportunities for optics in general and optical computing in particular to play a critical role in the development of 3-D machine vision systems.

8. REFERENCES