Understanding Depth

Range Image Sensors and 3D Data Acquisition

For us human beings, it is easy to understand pictures. We are able to estimate depth easily by using the information given by motion or the disparity between the two images seen with our two eyes. In contrast to this, – even with the incredible growth of computational capacity and power in the last years – computers are not able to understand images in every context. An image provided by a common camera depicts the intensity distribution of the scene without any 3D data. One of the main problems in the research field of image understanding is the lack of three-dimensional (3D) data. The interest in range images for high-end research projects and applications has increased dramatically in the last decade. One way to capture 3D information is the ability to directly acquire range images with laser range sensors. These sensors deliver a discrete representation of the surface in the scene, which offers a greater chance for computers to increase the level in image understanding.

A wide variety of laser range scanners are available in the market. Range images differ from "usual" intensity images in the consideration of additional depth information. For depth measuring two major principles — triangulation and time-of-flight (TOF) — are used in many fields of research and applications. TOF and phase measurement methods are long range technologies and triangulation based methods belong to close range methods.

The non-contact approach is the most important aspect of visual range measurement methods. This allows for the measurements of substances which may be hot, chemically aggressive, sticky or sensitive, provided that sufficient light is reflected back from the surface. There is no possibility of any damage or wastage to the object. In addition, these techniques are relatively fast and economical. On the other hand, visual non-contact methods are vulnerable against transparency and multiple reflections. Different methods exist for the visual data acquisition and even range data is obtained in many different ways. In general, the range data acquisition is separated into two categories – active and passive range imaging, respectively. In the passive method, no special light is required in addition to the ambient light for illumination. The most common data sources for industrial applications are still passive camera systems.

In active range imaging, a dedicated and well defined light source (e.g. laser light source) is used in cooperation with a visual capture device. At the moment, these active sensors are superior to other industrial measurement methods regarding their accuracy, cost and robustness compared to stereo camera systems. The well known methods "time-of-flight" (TOF) and "triangulation" are part of the active methods. In the active triangulation scheme, the scene is illuminated by a laser source from one direction and viewed by a sensor from the other direction. TOF measures the time of a reflected laser pulse to determine the distance to an object.

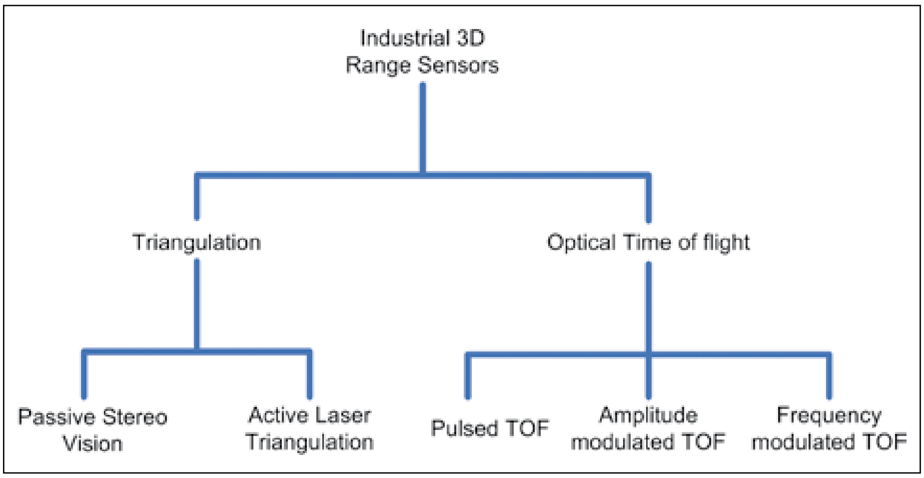

Fig. 1: Industrial 3D Range sensors

The advantages of the active methods are the production of dense sampling points and the high robustness and precision compared to the passive methods. However, additional light sources must be added in the scene and the methodology does not correspond to human stereo vision.

Figure 1 shows the variety of different measurement technologies. TOF and phase measurement methods are long range technologies (over 1 m) and triangulation-based methods belong to close range methods. Most long range measurement sensors are used for surveying and mapping in architectural and cultural heritage, geodesic laser scanning, archeological heritage conservation, and the 3D scanning of buildings. Active close range 3D sensors are often used in quality management, reverse engineering, visualization and 3D modeling, and have become one of the major aspects of computer vision and robotics.

The process of reconstructing an existing object (reverse engineering) which gives all the information about the shape and size of the object is very important for industrial applications. Quality management can use the Computer Aided Design (CAD) model of the product through range imaging to ensure the uniformity in shape and size.

Triangulation

The principle of triangulation is based on simple geometrical constraints. An active triangulation system consists of a light source and a receiving unit. There are triangulation-based sensors existing that deliver one-dimensional, two-dimensional and range image data. Depending on the resulting dimension, the active triangulation methods can be separated in Single Spot Triangulation, Sheet of Light Triangulation and Coded/Structured Light Triangulation.

Single Spot Laser Triangulation is based on simple trigonometric equations. A laser spot is projected onto the object. The scene is recorded with a CCD array. If the distance changes to the laser, the position of the reflection in the CCD array also changes. Due to geometric relations, the changed distance can be calculated the other way round.

The distance to the object in figure 2 can be calculated by the following equation:

$$x = D\frac{\frac{x_0}{D} + \frac{x' - x_0}{f}}{1 - \frac{x_0}{D}\frac{x' - x_0}{f}} \qquad (1.1)$$

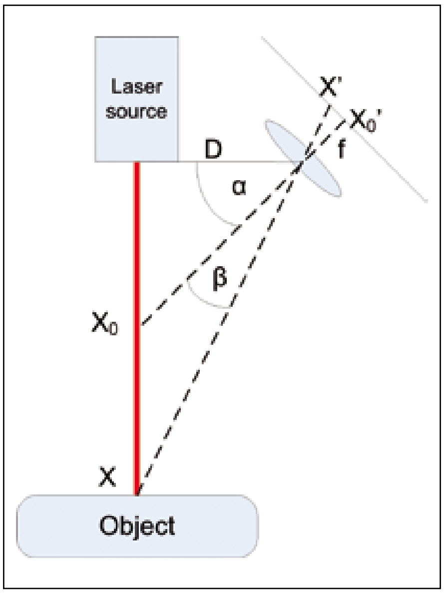

Fig. 2: Triangulation principle

Figure 2 shows the configuration for a reflected laser spot and a CCD-array, which can be used for determining a one-dimensional distance value. The accuracy (usually ~1:1000) depends on the distance between the laser and receiving unit and the object distance. Active triangulation is usually used in measuring a range of 0.1–5 m. Measurement times of less than 10 ms are common, allowing real-time study of moving or vibrating objects. Active triangulation can also be extended to a laser line and CCD-matrix, resulting in a two-dimensional distance array.

In this application the triangulation system acquires a fully two-dimensional profile. A camera captures the projected line. With the help of the geometric configuration the distance can be acquired. For each column Xi in the camera matrix, the geometrical considerations (Equation 1.1) of single spot triangulation are applied.

A further method of triangulation sensors belongs to structured or coded light techniques. A coded pattern – such as a gray coded or phase-coded pattern — is used to illuminate the scene for acquisition. In a growing number of industrial applications, structured light approaches are realized. For the acquisition of 3D scenes, no scanning or moving profile sensors are required, so this method is usually faster than other 3D scanning techniques.

In the last few years, the accuracy of structured light range data acquisition has increased up to 1 µm. More and more companies offer promising solutions. Unfortunately, this measurement technique still suffers from ambient light influences, complex calibration and the lack of a ready-to-use solution for industrial environments. Several 2D trian-

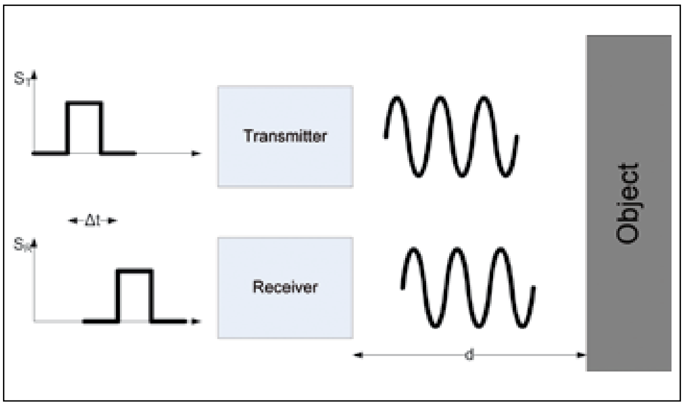

Fig. 3: Pulsed TOF measurement principle

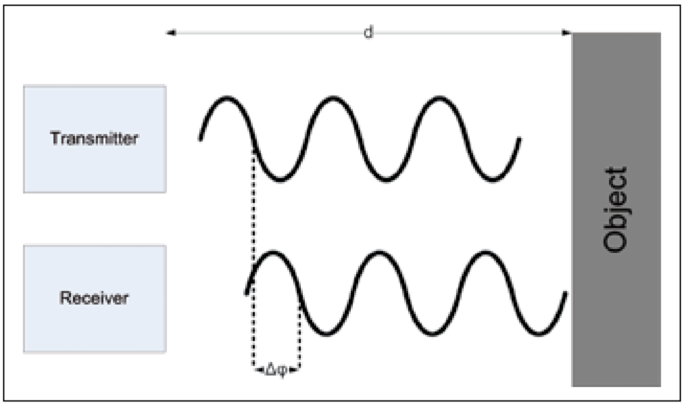

Fig. 4: Modulated Continuous Wave TOF measurement principle

gulation-based laser range sensors are available for industrial applications. Most of these are close range sensors with a laser stripe source and a camera inside a fixed frame without the need of calibration.

Time of Flight

Time-of-flight (TOF) laser distance sensors measure the distance between the object and the light source along a light beam. Time-of-flight systems send out a light beam towards an object. The light is diffusely reflected by the surface and a part of the light returns to the receiver. The time that light needs to travel from the laser diode to the object surface and back is measured. When the light pulse is emitted a high accuracy stopwatch is started. The light pulse travels to the target and back to the receiver. When the light pulse arrives, the stopwatch is stopped and the time of the flight is calculated. With the known speed of light the distance to the object is determined.

Figure 3 shows the TOF configuration. In practice, the active light source and the receiver are located very closely to each other. Illumination and observation directions are approximately collinear, so this avoids shadowing effects. The existing methods relying on the principle of TOF can be separated in Pulsed TOF and Modulated Continuous Wave TOF.

In the case of pulsed TOF, the travel time is directly proportional to the distance traveled, taking into account the velocity of light in the involved medium using the following equation:

$$d = \frac{c\,\Delta t}{2n} \qquad (1.2)$$

It applies here: c is the velocity of light and Δt is the time taken by the signal to travel from the source to the object and back. The involved medium is integrated as the refraction index n. The equation contains a factor of 0.5 because of the way to the object and back. Theoretically, the accuracy of the depth measuring is independent from the distance of the object to the camera and only depends on the precision achieved measuring the travel time. But precision in the millimeter and sub-millimeter range requires pulse lengths of a few picoseconds and the associated electronics. Mainly, the pulse rate influences the maximum range for TOF sensors. To send out a new pulse, the receiving unit has to wait for the last echo arriving from the object. Some long range sensors use the pulsed TOF method to measure distances up to a few kilometers for cartographic mapping. At ranges of a few kilometers and above, a different problem arises: at such distances the amount of reflected photons that reach the detector is very small. The sensitivity of the receiving unit and the power of the emitted light pulse are limited in all real range sensors. This leads to a limitation of the range of these sensors. A variation of the time-of-flight distance measuring is the measuring of the phase shift. This method effectively measures the difference between emitted and received signals. A continuous wave (CW) laser emits light continuously and, therefore, is called a CW-laser.

As shown in figure 4, the distance information is extracted from the received signal by comparing its modulation phase to that of the emitted signal. The range of phase measurement TOF sensors depends on the wavelength of the modulated signal so the resolution of these sensors can be improved if signals with short wavelength are used. That being said, this leads to a reduced maximum range of phase shift measurement. The maximum unambiguous detectable phase delay is a full cycle of the modulation period. For phase shifts over 360°, however, an unequivocal determination of the distance is not trivial, which means that the maximum useful measurable distance is half of the distance traveled by light during one period. This continuous wave can be modulated in the amplitude or the frequency. An amplitude modulated continuous wave (AMCW) is often a sinusoid wave and this wave is modulated in amplitude by varying the power. Frequency modulated continuous wave (FMCW) distance measurement is achieved by measuring the phase of the modulation of the transmitted light. Phase shift measurement has a higher precision than that of conventional TOF measuring. In practice, a combination of these two procedures is often used. This method is typically used for measurement distances of a few tens of meters. The accuracy is between a few millimeters and two or three centimeters, depending on time measurement and on the distance between the object and the scanner (object distance). The TOF-principle is extended for industrial range image data acquisition by moving the laser line or by putting many laser emitting/receiving units together.

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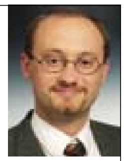

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