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A Review of ToF PMD Camera

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ABSTRACT: The time-of-flight (ToF) camera is a basic component for the range measurement and Photonic Mixer Devices(PMD) uses this principle for constructing a 3-dimensional image. PMD combines the advantages of active sensors and provides accurate distance measurements and camera based systems recording a 2D matrix at a high frame rate. This paper focus on the different characteristics of this type of sensor such as integration time, modulation frequency and operating principle of the ToF Cameras. Different advantages such as registered depth and intensity data at a high frame rate, compact design, low weight, and reduced power consumption have motivated their increasing usage in several research areas, such as computer graphics, machine vision, and robotics are discussed.

KEYWORDS: Photonic-Mixer-Device(PMD), Phase Shift Algorithm, Time-of-flight(ToF), 3D- Reconstruction,PMD Applications,Motion Artifact,

I.INTRODUCTION

The PMD sensor offers a way to capture 3D images without complex electronic system design. The sensing of optical light input and demodulation (by correlation) with reference modulation signal is done at the chip level. The distance and amplitude map can be obtained directly from camera

Basic Principal of ToF Camera

The Photonic Mixer Device (PMD) works on the principle of Time-Of-Flight (TOF). The basic principle of TOF is to calculate distance of an object based on the time required for a light pulse to travel towards the object and back to sensor after reflecting off the object. With the knowledge of speed of light, the distance can easily be calculated. The accuracy of measurement depends on the accuracy of time measurement. Hence, for accuracy of 1mm in distance measurement, the time measurement should have accuracy of

$$\frac{2d}{c} = \frac{2 \times 1 \times 10^{-3}}{3 \times 10^{8}} \approx 6.6ps \quad \dots (1)$$

The TOF techniques which implement direct time measurement for measuring distances are known as pulsed modulation. These techniques require large bandwidth since it needs to produce very short light pulses with fast rise and fall times, which are necessary to assure an accurate detection of the incoming light pulse. This leads to restriction on the light source that is used for scene illumination (only lasers can be used for high bandwidth and high output power for light source)[1].

The PMD sensors use continuous-wave (CW) modulation. This does not require high bandwidth. Any light source can be used since it does not require high rise and fall times. The CW-modulation involves modulating the light source before transmission. The modulated light reflects back from the object and is received at the sensor. The received optical signal is correlated with the modulating signal which was used to modulate the transmitted light signal. The phase difference between sent and received signals is measured which corresponds to the distance between the sensor and the object. Since the correlation takes place between signals of same frequency, the type of modulation mode is called homodyne operation. The homodyne operation works with one single frequency and does not necessarily require a large bandwidth[2].

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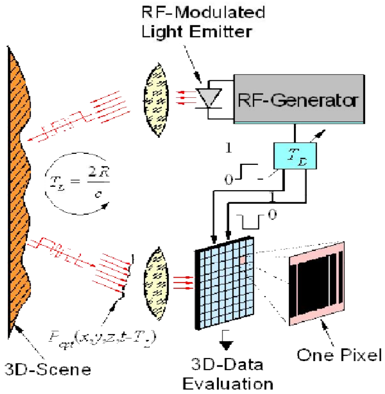

Fig. 1 Time-Of-Flight (ToF) principle [1]

Thus, summarizing the whole operation, the operation of PMD sensor involves transmission of modulated light. The modulated light reflects off the object and is incident on the receiver (PMD sensor). The received light (optical) signal is correlated with the modulation signal. The phase difference between the two signals, which corresponds to the distance between object and sensor, is measured using the phase shifting technique. The correlation of the signals takes place inside the PMD sensor cell. The charge levels (raw data) generated in the charge wells, due to correlation of the signals, are read out and the amplitude (signal strength) and distance information is calculated from it.The calculation of the distance, amplitude and phase difference between signals is as follows:

Traveling at speed of light c, the light signal reflects off the object and gets back at the camera after a time of flight with a phase shift of Φ. Suppose a sinusoidal signal as a modulation signal. If the modulation signal g(t) and received signal s(t) with modulation amplitude 'a' and phase shift 'Φ' is given as

$$g(t) = \cos(\omega t) \qquad \ldots (2)$$

$$s(t) = 1 + (a \times \cos(\omega t + \emptyset)) \qquad \ldots (3)$$

The correlation of the signal results in

$$r(\tau) = \left(\frac{a}{2}\right) \times \cos(\emptyset + \omega\tau) \qquad \ldots (4)$$

This is the expression for correlation between the received optical signal and reference modulating signal. Notice that it is a function of phase difference between the two signals and modulation amplitude. The phase difference and amplitude can be extracted by N-phase shifting technique. This requires sampling the correlation function at N different points[8].

For 4-phase shifting technique, we sample the correlation function at ωτ0=0°, ωτ1=90°, ωτ2=180° and ωτ3=270°. Substituting the values in expression for c(τ), we get:

$$r(\tau_0) = \left(\frac{a}{2}\right) * \cos(\Phi) \qquad \ldots (4)$$

$$r(\tau_1) = -\left(\frac{a}{2}\right) * \sin(\Phi) \ldots (5)$$

$$r(\tau_2) = -\left(\frac{a}{2}\right) * \cos(\Phi) \qquad \ldots (6)$$

$$r(\tau_3) = \left(\frac{a}{2}\right) * \sin(\Phi) \qquad \ldots (7)$$

From these equations, the amplitude and phase can be calculated as:

$$\Phi = \tan^{-1}\left(\frac{r(\tau_3) - r(\tau_1)}{r(\tau_0) - r(\tau_2)}\right) \ldots (8)$$

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$$a = \frac{\sqrt{[r(\tau_3) - r(\tau_1)]^2 + [r(\tau_0) - r(\tau_2)]^2}}{2} \quad \dots (9)$$

In general, for a N-phase shifting technique, the correlation function is sampled uniformly at 2πn/N points, where n = 0, 1,…, N-1. The amplitude and phase for this case is calculated as follows:

$$a = \frac{2}{N}\sqrt{\left[\sum_{k=0}^{N-1} r(k) * \cos\left(\frac{2\pi k}{N}\right)\right]^2 + \left[\sum_{k=0}^{N-1} r(k) * \sin\left(\frac{2\pi k}{N}\right)\right]^2} \quad \dots (10)$$

$$\Phi = -\tan^{-1}\left(\frac{\sum_{k=0}^{N-1} r(k) * \sin\left(\frac{2\pi k}{N}\right)}{\sum_{k=0}^{N-1} r(k) * \cos\left(\frac{2\pi k}{N}\right)}\right) \quad \dots (11)$$

The distance is calculated from phase as follows:

$$D = \frac{c \times \Phi}{4\,\pi f_{mod}} \quad \dots (12)$$

Knowledge of modulating frequency allows us to calculate the distance of an object from sensor by detecting the phase shift undergone by the optical signal after reflection off the object. The maximum distance that can be calculated is when$\Phi = 2\pi$.

$$D_{max} = \frac{c}{2 * f_{mod}} \quad \dots (13)$$

Hence, for a given modulating frequency, the maximum distance that can be calculated is finite and fixed. This range from 0 to Dmax is called the unambiguous range. Objects beyond this range are measured with ambiguity. The amplitude output for these objects is relatively smaller than for objects within the unambiguous range. Hence, the amplitude output can be used as a metric to check for unambiguous distance measurement.Thus, the distance and amplitude can be measured from the correlation of transmitted and received signals using the phase shifting technique.

II. RELATED WORK

An unique image sensor called – Photonic Mixer Device (PMD) – has been developed by Prof. R. Schwarte, at the institute of signal processing of university Siegen, ZentrumfuerSensorsysteme (ZESS) and later on S-TEC GmbH (since 1997). In 2000, the first solid state camera based on PMD technology was developed. The 19k-S3 was the first commercially available 3D-ToF (Time-of-Flight) chip for camera developers and system integrators. It contains 160X120 pixel array. The highest camera resolution now available is the PMD 100K camera, which contains pixels in an array grid of 352X288. The PMD sensor is able to provide distance (depth) information of the scene along with amplitude image of the scene, which is equivalent of 2D image acquired by standard CCD cameras.

The PMD sensors are relatively new when compared to CCD cameras which have been in use for decades. Hence, there is relatively less number of algorithms and applications developed for PMD sensors than for CCD / CMOS cameras. However, due to the availability of depth information along with 2D information of the scene, development of applications like object recognition, control and navigations, etc. is going to be less challenging when such sensors are used. Hence, it is possible that such 3D sensors will replace the use of conventional cameras in fields where a fast and reliable acquisition of 3D data has become a main requirement for future developments, for e.g. in industrial and automobile industries[1].

Schmidt [2] proposes a method handling motion artifacts as disturbances in the raw data. Motion artifacts are calculated for each phase image using a temporal derivative. High temporal derivatives of the raw data are then replaced by previously valid values. An advantage compared to Hussmann et al. is the arbitrary degree of freedom.

Hussmann et al. [3] introduce a motion compensation for linear object motion on a conveyor belt. Areas of motion artifacts are identified using phase image differences. These areas are binaries for each individual difference image using a threshold. The length of motion is determined by processing each line of the binary.

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Tobias Möller et.al. [5]explains the basic principle of the PMD technology and solution to the backlight illumination problem by inventing the SBI - Suppression of background illumination technique and also explains the different technical implementation of PMD Technology for different indoor and outdoor application. Stephan Hussmann and TorstenEdeleret et.al [8]. Further explains a pseudo 4-phase shift algorithm to improve the measurements of the PMD Camera. TorstenEdeleret also explains the motion artifact and a simple algorithm which can detect the motion artifact pixel for object moving on conveyor belt.

III. PMD WORKING PRINCIPLE

This section will explain the working mechanism of a PMD sensor and how the above measurements are carried out in PMD sensor. The cross-section of a simplified two modulation gates PMD-structure, realized based on standard CMOS technology, is shown below on Fig. 2.

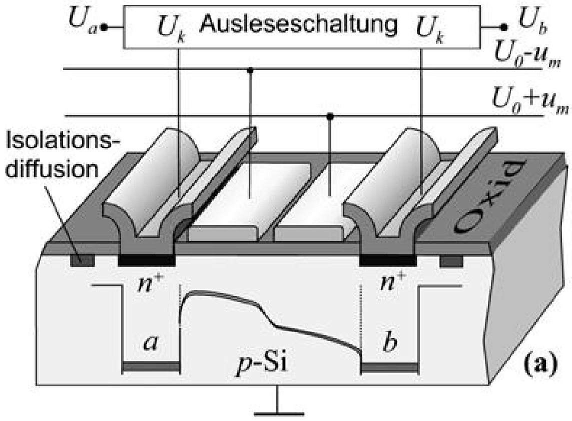

Fig. 2 PMD pixel architecture [2]

The “Uo – um” and “Uo + um” signals in the Fig. 2 are the modulating signals (similar to g(t) signal used in above analysis). They are connected to two poly-Silicon gate. The gates are isolated from the p-type substrate by an oxide layer. This structure forms a MOS capacitor. The two photogates are called channel A and channel B. The two modulating signals “Uo–um” and “Uo+um” are always out of phase with each other. This area forms the optical sensitive zone of PMD for receiving modulated optical signals. Adjacent to them are two reverse biased diodes with common anodes on the ground potential. They form the charge wells in PMD for collecting the charges generated, when light signal is incident on the cell. The diodes are also called as read-out diodes, since they facilitate in measuring the PMD charge accumulated in charge wells. This is performed through read-out circuitry shown in the figure above. The Ua and Ub terminals are the outputs of PMD sensor which gives the readings for channel A and channel B.
The advantage of using two channels and two charge wells is that when ambient light is incident on the cell, it generates equal amount of charges in both charge wells. Hence, the effect of ambient light can be removed simply by subtracting the outputs of the individual channels[2].

When light is incident on the optical sensitive zone, electron-hole pairs are generated. Depending upon the modulation signal applied, the potential gradient as shown above is set-up. The electrons drift either left to right or right to left and are collected in the charge wells. The read-out diodes provide the charge accumulated in the corresponding wells. The sum of channel data gives the total photo current corresponding to the optical intensity, while the differential output of both channel data stands for the correlation product of the reflected optical signal and the reference signal. The amplitude data of PMD sensor is calculated from this difference data.

The correlation in a PMD cell is said to occur when the photo gates are modulated with reference signal and light signal is incident on it. At this place, the correlation of optical and electric signal takes place. The amount of charge generated in a given channel depends on the amount of light incident on it and the modulation signal applied.

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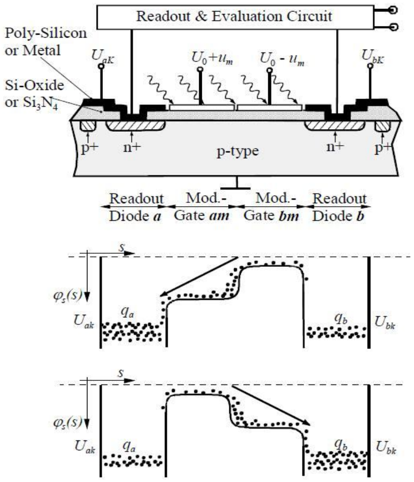

Fig. 3 PMD Pixel Channel Separation [2]

The time during which the channel data is accumulated is called the integration time. The modulating signal is a high frequency signal such that there are many cycles of modulating signal is one integration time. The charges generated in the channels get accumulated in the charge wells for every cycle of modulation signal. The effect of integration time on the output of PMD sensor is different at different value. At very small integration times, the noise overrides the input signal. Hence, no intelligible output can be obtained. In the operating region, the PMD output increases with increase in integration time. In this region, the performance of PMD sensor gets better with higher integration time. For integration times outside the operating region, the output of PMD sensor begins to decrease. This is because of saturation of charge levels in the PMD cell. For higher integration times, the performance of PMD sensor degrades.

IV.STEPS FOR IMAGE ACQUISITION

Consider a square wave modulating signal with amplitudes 0 and 1. The incident optical signal is also a square wave with appropriate phase shift. When the gate voltage at the photo is 1, the channel is ready to accept photons (light energy), while, when the gate voltage is 0, the channel does not accept light signal. In this case, it can be considered that the shutter for the given channel is closed. The amount of charge generated in a given channel depends upon the phase shift between the light signal and the modulating signal. As the phase difference between the signals varies, the overlap between the two signals also varies. For different amount of phase shift, the charge generated will be different; for 0 phase shift, the amount of charge generated will be maximum[3].

Considering a 4-phase shifting technique, when a frame is taken, the following steps are performed:
Light signal is modulated with modulating signal (0 phase shift) as shown in Fig. 4(a). The modulated signal is transmitted towards the object. The reflected modulating signal is incident on the PMD sensor cell. The received signal and the modulating signal are correlated (opening and closing of gate by modulation signal when light signal is incident accomplishes this). The channel A and channel B data are read as channel data for 0 phase shift[9].

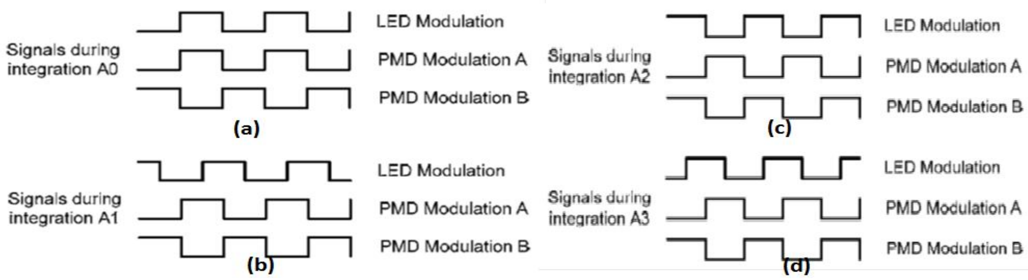

Fig. 4.4-Phase capture (a) phase0 (phase difference 0 between LED modulation and PMD modulation signals) (b)phase 90 ,(c) phase 180, (d) phase 270.

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The light signal is now modulated with modulation signal which is shifted by 90°. The received light is correlated again with original modulating signal (there is no phase shift in modulation signal here) as shown in Fig 4(b). The channel data are read as channel data for 90° phase shift.The process is repeated by modulating the signal using 180° and 270° phase shifts of modulating signal. The modulating signal is phase shifted only for modulating the light signal. The correlation of received signal is carried out with the original modulation signal. The channel data are read out for 180° and 270° phase shifts.

The channel A data and channel B data are subtracted and the difference is stored for selected integration time. These differences are the samples for correlation function at $\omega\tau0=0°$, $\omega\tau1=90°$, $\omega\tau2=180°$ and $\omega\tau3=270°$. Distance can be calculated by equation 14

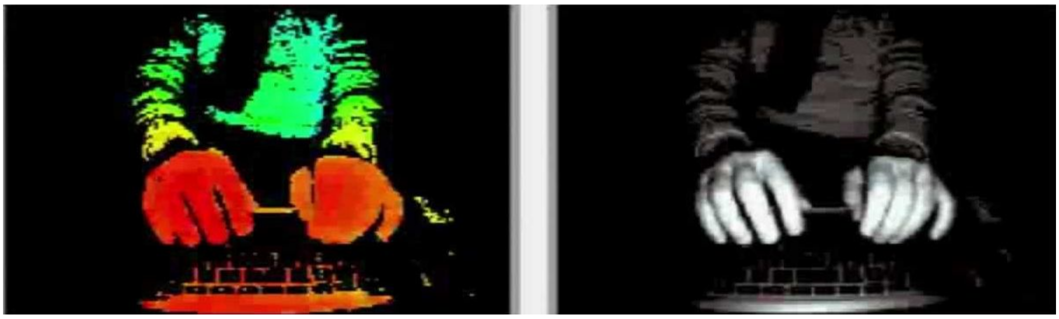
$$\Phi = \tan^{-1}\left(\frac{r(\tau_3) - r(\tau_1)}{r(\tau_0) - r(\tau_2)}\right) \quad \ldots (14)$$

$$D = \frac{c * \Phi}{4\,\pi\, f_{mod}} \quad \ldots (15)$$

and amplitude Image can be calculated by equation 17

$$A = \frac{\sqrt{[\,r(\tau_3) - r(\tau_1)]^2 + [\,r(\tau_0) - r(\tau_2)]^2}}{2} \quad \ldots (16)$$

Where$r(\tau)$ is the correlation sample, given here by the difference of channel A and B data.



(a) (b)

Fig 5. PMD Camera Images (a) distance Image (b) Amplitude Image
[Source : http://www.pmdtec.comnews_mediavideocamboard_nano.php]

V.APPLICATIONS

The ToF camera has been an attractive solution, due to its compact construction together with high accuracy and frame-rate, and easy-of-use, for wide range of applications from Computer human interaction,Automobile, Industries and construction. Some of these are discussed below

Computer Human Interaction:
Due to compactness and USB interface to PMD cameras it is easy to interface the device with personal computers. PMD SDK which provides the basic functionality to grab distance, amplitude, grayscale and 3D coordinate of the scene in front of camera can be used to develop different application which can depend on human Gestures. Gaming Industry is also using this technology for developing the games with live interaction.

Industry Automation:
A vast applications ranging from Automatic Milking Robot where robot use ToF camera for teat Detection and tracking, Bottle filling plants where cameras can be used for finding missing bottles in bottle containers while packing

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them. Application such as objectcountingin production line of an Industry. These cameras can also be used in modelling the different Structures in Construction industries.

Automobile Industries:
Application such as Collision Avoidance,Blind Stop Detection, Automatic GuidanceVehicle, where camera can be used to create the scene around the car. Heavy Duty Vehicles can use these cameras to detect object behind. These cameras can also be used in Agriculture for guiding automatic ploughing, sowing and crop cutting vehicles.

Along with these there can be many applications such as Area Surveillance, Traffic Surveillance for detecting object, speed and direction of vehicle, Volume Calculation of the object, 3D- model creation of the building, etc.

VI. DISCUSSION

PMD Camera measures distance with indirect ToF Technology. Basically distance is proportional to the measured phase shift between modulation signal and light signal. The complex correlation of this two signal to find the phase shift is implemented in Silicon(PMD Chip) making the system less complex and high resolution images can be obtain. The Image Processing chain of the ToFcamera is shown in Fig 6.

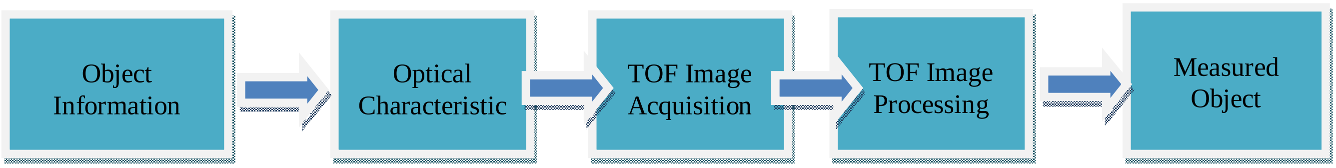

Fig 6. Image Processing bocks for PMD-TOF Camera [7]

Object Information generally defines the scene in front of the camera. Optical characteristics of the PMD camera are determined by the Field of view of the camera which basically ranges from 30- 60 degree for different PMD cameras. TOF Image acquisition blocks deals with Integration Time and the frame rate of the camera and responsible for image quality lesser the integration time more noise in the distance value. TOF Image Processing block calculates the Distance and Amplitude values from raw phase values captured by the sensor. Measures object information block displays the different types of Images[7].

Characteristics of PMD Camera:
Two parameters can be adjusted, the modulation frequency and the integration time. Although it is possible to change modulation frequency but generally only integration is changed for better quality image. PMD change work at different modulation frequencies and these frequencies determines the ambiguous distance range of the camera. Ambiguous Range determines the maximum range that camera can detect. The other variable parameter is the integration time, Integration time is the most critical internal parameter of the PMD camera. It describes the time period in which incoming photons are detected for one measurement cycle, in order to derive phase shift and the corresponding distance. If the integration time is too low, the amplitudes of related pixels decrease and distances for distant objects cannot be measured. On the other hand, if the integration time is too high, oversaturation is observed and measurements fail, too. Therefore, a major challenge in obtaining appropriate range images is to find adequate integration time values for particular scene[6].

SBI - Suppression of background illumination:
The light receive by the PMD sensor while capturing image is the mixture of ambient light and modulated light from light source.Optical filtering and bursting of light sources might not be sufficient to reduce disturbing uncorrelated sunlight. The remaining background illumination can still saturate the sensor for typical integration times which can lead to a decrease of accuracy or pixel failures.To eliminate uncorrelated signals which are distributed on both readout sides equally, additional compensation sources have been added. These sources inject additional charges in both readout terminals in order to instantaneously compensate for the saturation effects of uncorrelated signals during the integration process. This compensation means that the dynamic range of the following readout stage can be completely used by the correlated signal information only. These will increase the dynamic range of the camera[5].

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Motion Artifact:

The distance image is generated from four phase measurements from PMD camera, the camera suffers from the motion artifact problem. This problem occurs because the four phase readings are taken one after another sequentially. Hence, the phase readings are not taken for the same distance. Since, all the four phases are used for back-calculating the distance, the distance calculated is incorrect. This incorrect pixel are called as Motion Artifacted Pixel[9]. In static scene all the pixel see the same distance at all phase measurement and hence no pixel suffers the motion artifact where as in dynamic scene where object is in motion the pixel see the edge of the moving object see different distance during phase capture due to inter- frame motion of the object. These lead to the incorrect estimation of the distance on these pixels. These incorrect estimated pixels vary in distance by a very large amount as the distance calculation formulae contain an arc tan function which is non-linear in nature. Currently research is going on to detect motion artifact pixels for reliable distance measurement in dynamic scene.

With all above characteristics and features PMD cameras are compact, provides real time frame rate, accurate measurement, high dynamic range, SDK for Application Development, Interfaces such as USB, Ethernet to interface with other systems.

VII.CONCLUSION

Time-Of-Flight systems based on the PMD-principle give the possibility of fast 3D measurement with customizable resolutions depending on the application. This contribution helps one to understand the basic principleand different characteristics of the PMD Technology along with different applications in different domain.Different characteristics such as integration time, modulation frequency which can be used to configure the camera for different FOV and better distance resolution required of the application development. Ambient light suppression and SBI features makes camera robust to work in heavy ambient light which can be very useful for outdoor application. This camera provides multiple images which can be used for development of different algorithms, feature extractions, 3D reconstructions. Some of the challenges that need to address are resolution of image which is low as compared to 2D cameras, noise in pixel at low integration time and saturation at high integration time, ambient light noise and motion artifact problem. Advantages of this type of sensors are multiple, as demonstrated in the previous sections: they are compact and portable, easing movement; they make data extraction simpler and quicker, reducing power consumption and computational time which motivates to develop real time application with these cameras.

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