State of the art modulator approaches for Continuous Time-of-Flight range finding

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An overview is given of different state of the art modulator approaches useable as demodulating component in Continuous Time-of-Flight range finding. The first is a spatial optical modulator which can be used in conjunction with a conventional image sensor; the second is a single bulk device combining both optical detection and modulation in the substrate. A third performs optical detection and modulation by combining fast conventional photo-detectors with subsequent analog circuitry to achieve modulation and amplification. The different design and implementation challenges are discussed and the properties of the different approaches at both sensor level and 3D-data post processing level are presented.

Continuous Time-of-Flight range finding

A typical range finding system based on Continuous Time-of-Flight (CTOF) is shown in figure 1. A first part of the system is a modulated light source, preferably LED's modulated at frequencies between 1MHz and 100MHz and emitting in the near infrared (NIR). This modulated signal is sent to a scene and the reflections are focussed by a lens on a second part. This second part is a detector-array which converts the optical

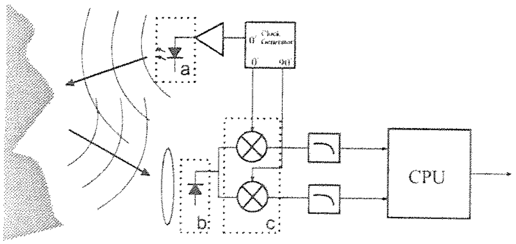

Figure 1: Typical Continuous Time-of-Flight system with three main parts a.Active intensity modulated illumination; b.detection stage; c.(de)modulation stage.

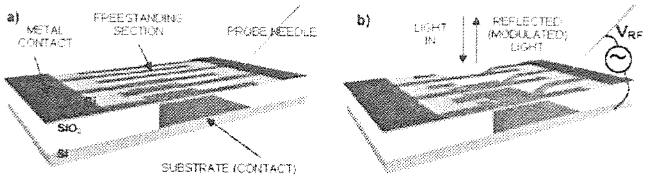

Figure 2: a.optical modulator in SOI with metal contacts and underetched (freestanding) diffraction grating section b.principle of operation: the RF-voltage deforms the diffraction grating and reflected light is modulated.

signals from the scene to electronic signals. The third part is a optical, electro-optical or electronic modulator which demodulates the received signal with the original sent out signal to extract the phase-shift, and hence the traveling time, of the reflection. Depending on the type of modulator, modulation occurs prior, during or after detection, giving rise to very different system topologies with each its specific advantages and drawbacks. The first part of the paper will discuss the state of the art modulators used in the different approaches, while the second part will highlight the impact of the chosen topology on the resulting 3D range measurement.

Spatial Optical Modulator approach

The first approach combines a spatial optical modulator, which produces a demodulated optical signal, with a conventional detector. Since the frequency of the modulation is required to be in the MHz-range and the used carrier at wavelengths ranging from 800nm to 1μm the applicable technologies are limited. Well established technologies such as liquid crystals [1] and MEMS micromirrors [2] tend to be slower than 1 MHz. To meet the necessary modulator requirements we are currently developing the device shown in Figure 2. A diffraction grating in SOI (Silicon-on-Insulator) is underetched, hence creating a parallel series of freestanding ribbons. By applying a voltage between the ribbons and the substrate the beams are pulled towards the substrate. This way the diffraction grating is tuned at the natural frequency of the ribbons (typically MHz range) and the reflected light is modulated [3]. Mature SOI-technology now provides a platform for diffraction gratings with subwavelength period which enables the exploration of the assets of strong subwavelength period diffraction effects.

Bulk demodulating optical detector approach

The second approach integrates the modulator and the detector in a custom solid state photonic mixer. We developed a solid state photonic mixer, called Current Assisted Photonic Demodulators (CAPD), based on the creation of alternating electric fields in substrate by injecting a majority carrier current. The CAPD device has already been reported in [4, 5]. The important features of this type of device are high responisity at NIR and sufficient bandwidth (up to 70MHz from [6]). At 20MHz modulation frequency the modulation contrast exceeds 90%. Integrating pixels using CAPD-type detector have been reported in [6] measuring $30\mu \times 30\mu$ with a FF of 75%.

Electronic approach

A third approach performs the modulation after detection. The modulated optical signal is captured by a detector with high detection bandwidth and converted into a high frequency electronic signal. This signal is then processed and mixed using analog circuitry. In [7] a PIN-bridge sensor was reported combining a PIN diode with an electronic modulator. However it must be noted that additional noise is added to the measurements, either by the transistors or by repeatedly switched capacitors. A pixel was reported measuring $250\mu \times 200\mu$ with a FF of 16%.

Impact of modulator approach on range image quality

For comparison of the impact of the different modulator approaches on range image quality the optical environment, including sent optical power P_A, present background light P_{BGL}, scene and lens system, are assumed invariant. Furthermore it is assumed that the optical signal is intensity modulated using a square wave at a certain frequency f_m. The linearity of the resulting range values is not included in the comparison. It can be shown that in the case of square wave intensity modulation:

$$\delta D = \frac{c}{2 \times f_m} \times \sqrt{\frac{\frac{1}{q} \times (P_A + P_{BGL}) \times A_{pix} \times t_{int} + n_{system}^2}{QE \times k_{opt} \times C_{mod}^2 \times \frac{1}{q^2} \times P_A^2 \times A_{pix}^2 \times t_{int}^2}} \times f(\phi)$$

Where c is the speed of light, q is the elementary charge, A_{pix} is the pixel area, QE is the quantum efficiency defined as the product of Fill Factor FF and responsivity, t_{int} is the integration time, C_{mod} is the modulation contrast, k_{opt} the optical constant determined by the properties of the optical system comprised of lenses, diffuser, etc and n_{system} is the noise added by the measurement in electrons. $f(\phi)$ is a scalar function only depending on the measured phase-shift.

We can now compare the impact of the different modulator approaches on the range resolution δD^2. Firstly we should note that the modulation frequency f_m directly impacts the range resolution. The modulation bandwidth of the modulator stage should be as high as possible. Secondly, equally important is the modulation contrast C_{mod} which defines the efficiency of the modulation. The range resolution also has a square root dependence on the Quantum efficiency QE.

Currently both the modulation bandwidth and contrast (extinction ratio) of the spatial optical modulator are still insufficient. However there are a lot of advantages to this topology. Firstly the noise added by conventional image sensors is very low (down to 1.5 electrons!). Secondly, the lateral resolution of this type of topology is potentially extremely high (Megapixels), opening doors to spatial filtering techniques. If improvements can be made to both modulation bandwidth and contrast this topology will provide the best range resolution.

The solid state modulator approach is currently the more favorable topology due to high modulation bandwidth, reasonable contrast and good QE at NIR light. A small amount of system noise is added due to reset and read-out noise.

The performance of the last topology based on electronic mixing is mostly determined by the added system noise n_{system}. This noise is introduced by the transistors and switching of capacitors needed to perform the electronic modulation. Moreover these pixels have low FF and large pixel size, reducing the QE.

Post-processing

To further increase the range resolution one can use spatial or temporale averaging of N range measurements. These averaging techniques produce good results only in the case when the range measurements are nearly constant in some area, or in some interval of time. In practice, averaging techniques produce over smoothing of edges or motion blur in the depth sequences.
Our recently developed method [8] is situated in the wavelet domain and takes into account the correlations between luminance image, which has significantly higher PSNR, and uses the values of luminance to denoise the depth image. Pixel neighborhoods from the luminance image are grouped according to their similarity, and that information is used to determine the parameters for vector Wiener denoising. The main advantage of our method is that it does not lead to temporal smoothing (motion blur).

Conclusions

We have discussed the main possible modulator approaches to be used in Continuous Time-of-Flight ranging. The Spatial Light Modulator (SLM) which is being developed will provide the best range resolution if the goals of high modulation frequency and extinction ratio (contrast) can be met. Currently the most favorable topology is based on solid state demodulators. We developed the CAPD device, which integrate both modulation and detection, and provides high modulation bandwidth, acceptable contrast and good QE at NIR. Lastly a new method has been developed to denoise the range image using luminance information.

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