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Smart Sensors for 3D Digitization*

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Smart Sensors for 3D Digitization

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ABSTRACT

This paper presents our activities on smart VLSI opto-sensors for 3D vision. A description of the integrated devices jointly developed for industrial and scientific applications will be given. All the sensors presented here have been fabricated using standard CMOS technology that allows the monolithic integration of photo-sensors, together with readout circuits, and digital signal processors.

INTRODUCTION

Digital 3D imaging can benefit from advances in VLSI technology in order to accelerate its deployment in many fields like visual communication and industrial automation. The NRC and IRST groups are collaborating on a project that is targeted at the integration of key sensors. These sensors include the synchronization photodiodes based on integrated bi-cells [1] and the laser spot position measurement sensors [2]. These sensors could become an integral part of future intelligent digitizers that will be capable of measuring accurately and simultaneously colour (reflectance) and 3D. This, in turns, will accelerate the development of hand-held 3D cameras [3], and, multi-resolution random access laser scanners for fast search and tracking of 3D features [2]. All these digitizers will require a thorough **VLSI integration** of basic laser camera functions to achieve size and cost reduction and most importantly, higher performance.

COLOUR 3D IMAGING TECHNOLOGY

Machine vision involves the analysis of the properties of the luminous flux reflected or radiated by objects. To recover the geometrical structures of these objects, either to recognise or to measure their dimension, two basic vision strategies are available. The first strategy, known as passive vision, attempts to analyse the structure of the scene under ambient light. In contrast, the second, known as active vision attempts to reduce the ambiguity of scene analysis by structuring the way in which images are formed. By keeping the properties of invariance in rotation and translation of 3D objects, sensors that capitalize on active vision can resolve most of the ambiguities found with 2-D imaging systems. Moreover, with laser-based approaches, the 3D information becomes relatively insensitive to background illumination and surface texture. Complete images of visible surfaces that are rather featureless to the human eye or a video camera can be generated. Thus, the task of processing the 3D data is greatly simplified. Lidar-based or triangulation-based laser range cameras are examples of vision systems built around such strategy [4]. Active triangulation is used in applications as diverse as reverse engineering, wood measurement, 3D documentation of cultural heritage sites [5], inspection of printed circuit boards, and automatic robot welding. Two digital 3D imaging systems were developed and demonstrated at the National Research Council of Canada (NRC). They are the auto-synchronized principle [6] and the BIRIS [7] system. These range cameras provide registered range and intensity data for visible surfaces (either monochrome or colour). Figure 1 depicts the optical geometry of a range based on triangulation along with some of its position sensors. A 3D surface map is captured by scanning a laser spot onto a scene, collecting the reflected laser light from a different vantage point (triangulation), and finally focusing the beam onto a position detector. A similar geometry can be based upon the projection of a laser line instead of a single laser spot.

Geometric correction of the raw data gives two images in perfect registration: one with *x, y, z* co-ordinates and a second with intensity data representing the collected laser power from the scene. The laser beam can be of a single wavelength (visible or infrared) or composed of multiple visible wavelengths for the purpose of measuring the colour map of a scene (reflectance map).

LASER SENSORS FOR 3D IMAGING

It is within the scope of this project that collaboration between the two groups was initiated. The result of this work has provided unique sensors that will allow 3D digital imaging technology to face the challenge posed by the many emerging markets. This research and development work will also contribute to the advancement of knowledge in 3D digital imaging. The following sensors are targeted for integration into VLSI:

A) Synchronization circuit based upon dual photocells (bi-cell) --> This sensor ensures the stability and the repeatability of range measurements in environment with varying temperature. Discrete implementations of the so-called synchronization circuits have posed many problems in the past. A monolithic version of an improved circuit (smart) has been built to alleviate those problems [1].

B) Smart 3D position sensors --> Integration of most low level processing steps on a chip using advances in VLSI will allow digital 3D imaging technology to become widely accepted and accessible to research labs, universities, industries, hobbyists, and, also to the home. Currently, commercial photodiode arrays used in 3D vision sensors are intended for 2D imaging applications, spectroscopic instruments or wavelength division multiplexing in telecommunication systems. Their specifications change according to the evolution of their respective fields and not to digital 3D imaging. For instance, speckle noise dictates a large pixel size [8] that is not compatible with current 2D imaging developments (where pixels are getting smaller).

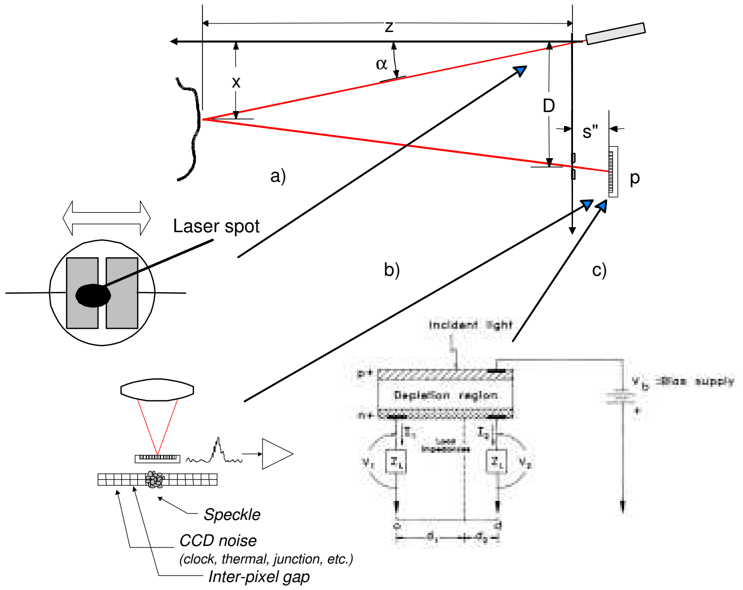


Figure 1 Optical geometry and photo-sensors used in a typical laser spot scanner 3D digitizer: a) dual-cell (bi-cell) for synchronizing a scanned laser spot, b) discrete response position sensor, and, c) continuous response position sensor.

PROPOSED SENSOR

Many devices have been built or considered in the past for measuring the position of a light beam. Among those, one finds continuous response position sensitive detectors (CRPSD) and discrete response position sensitive detectors (DRPSD) [9-20]. The category CRPSD includes lateral effect photodiode and geometrically shaped photo-diodes (wedges or segmented). DRPSD on the other hand comprise detectors such as Charge Coupled Devices (CCD) and arrays (1-D or 2-D) of photodiodes equipped with a multiplexer for sequential reading. One cannot achieve high measurement speed like found with continuous response position sensitive detectors and keep the same accuracy as with discrete response position sensitive detectors. On Figure 1, we report two basic types of devices that have been proposed in the literature. A CRPSD provides the centroid of the light distribution with a very fast response time (in the order of 10Mhz) [20]. On the other hand, DRPSD are slower because all the photo-detectors have to be read sequentially prior to the measurement of the location of the real peak of the light distribution [21]. People try to cope with the detector that they have chosen. In other words, they pick a detector for a particular application and accept the tradeoffs inherent in their choice of a position sensor. Consider the situation depicted on Figure 2, a CRPSD would provide A as an answer. But a DRPSD can provide B, the desired response. This situation occurs frequently in real applications. The elimination of all stray light in an optical system requires sophisticated techniques that increase the cost of a system. Also, in some applications, background illumination cannot be completely eliminated even with optical light filters. We propose to use the best of both worlds. Theory predicts that a CRPSD provides very precise measurement of the centroid versus a DRPSD (because of higher spatial resolution). By precision, we mean *measurement uncertainty*. It depends among other things on the signal to noise ratio, the quantization noise, and the sampling noise. In practice, precision is important but accuracy is even more important. A CRPSD is in fact a good estimator of the central location of a light distribution. Accuracy is understood to be the true value of a quantity. DRPSD are very accurate (because of the knowledge of the distribution) but can be less precise (due to spatial sampling of the light distribution).

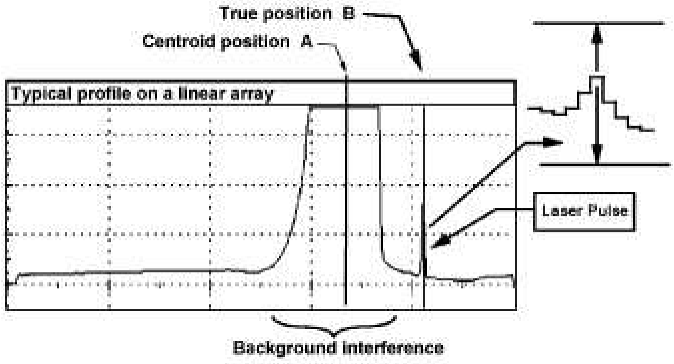


Figure 2 A typical situation where stray light blurs the measurement of the real but much narrower peak. A CRPSD would provide *A* as an answer. But a DRPSD can provide *B*, the desired response peak.

Their slow speed is due to the fact that all the pixels of the array have to be read but they don't all contribute to the computation of the peak. In fact, what is required for the measurement of the light distribution peak is only a small portion of the discrete detector. Hence the new smart detector. Once the pertinent light distribution is available, one can compute the location of the desired peak very accurately. Figure 3 shows an example of the embodiment of the new smart position sensor for single light spot measurement in the context of 3D and colour measurement. An object is illuminated by a collimated RGB laser spot and a portion of the reflected radiation upon entering the system is split into four components by a diffracting optical element. The white *zero order* component is directed onto the DRPSD, while the RGB 1st order components are directed onto three CRPSD which are used for colour detection. The CRPSDs are also used to find the centroid of the light distribution impinging on them and to estimate the total light intensity. The centroid is computed on chip or off-chip with the well-known current ratio method i.e. (I1-I2)/(I1+I2) where I1 and I2 are the currents generated by that type of sensor [20]. The centroid value is fed to a control unit that will select a sub-set of contiguous photo-detectors on the

DRPSD. That sub-set is located around the estimate of the centroid supplied by the CRPSD. Then, the best algorithms for peak extraction can be applied to the light distribution of interest, e.g. see [21].

IMPLEMENTATION AND EXPERIMENTAL RESULTS

We present here the architecture and preliminary experimental results of a first prototype chip of a DRPSD with selectable readout window. This is the first block of a more complex chip that will include all the components illustrated in Figure 3. The prototype chip consists of an array of 32 pixels with related readout channels and has been fabricated using a 0.8µm commercial CMOS process [22]. The sensor architecture is typical for linear array optical sensors [23] and is shown in Figure 4. The novelties implemented consist in a variable gain of the readout channels and a selectable readout window of 16 contiguous pixels. Both features are necessary to comply with the requirements of 3D single spot vision systems, i.e. a linear dynamic range of at least 12 bits and a fast readout. Of course, in the prototype, many of the signals which, in the final system are supposed to be generated by the CRPSDs, are now generated by means of external circuitry. As stated above the photosensor array contains 32 pixels with a pitch of 50µm, each pixel having a sensitive area of 48 x 500 μm^2. The large dimensions of the pixel are, required, on one side to cope with speckle noise [8] and, on the other side, to facilitate system alignment. Each pixel is provided with its own readout channel for parallel reading. The channel contains a charge amplifier (CA) and a correlated double sampling circuit (CDS). To span 12 bits of dynamic range, the integrating capacitor of the CA can assume five different values (CAP). In the prototype chip the proper integrating capacitor value is externally selected by means of the switches C0-C4. In the final sensor, however, the proper capacitance value will be automatically set by an on chip circuitry, on the basis of the total light intensity as calculated by the CRPSDs. During normal operation all 32 pixels are first reset at their bias value and then left to integrate the light for a period of 12µs. Within this time the CRPSDs and an external processing unit are supposed to estimate both the spot position and its total intensity and to feed those parameters to the window selection logic, LOGIC_A, and to the gain selection logic, LOGIC_B. After that, 16 contiguous pixels, as addressed by the window selection logic, are read out in 52µs, for a total frame rate of 64µs.

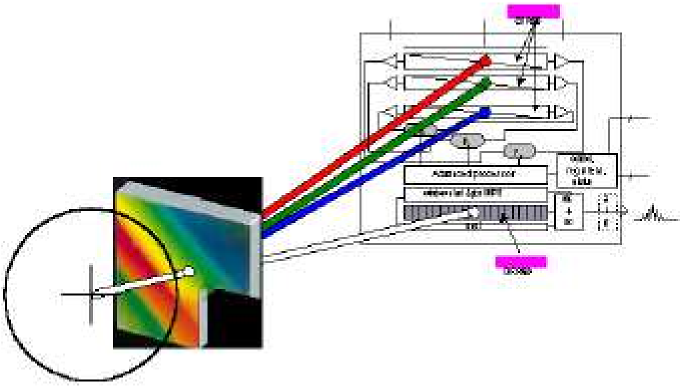


Figure 3 Artistic view of a smart sensor for accurate, precise and rapid light position measurement.

The window selection logic, LOGIC_A, receives the address of the central pixel of the 16 pixel and calculates the address of the starting and ending pixel. The analog value at the output of the each CA within the addressed window is sequentially put on the bitline by a decoding logic, DECODER, and read by the video amplifier. LOGIC_A generates also synchronisation and end-of-frame signals which are used from the external processing units. LOGIC_B, instead, is devoted to the generation of logic signals that drive both the CA and the CDS blocks. To add flexibility also the integration time can be changed by means of the external switches T0-T4. The chip has been tested and its functionality has been proven to be in agreement with specifications. In Figures 5 and 6 are illustrated the experimental results relative to spectral responsivity and power responsivity, respectively.

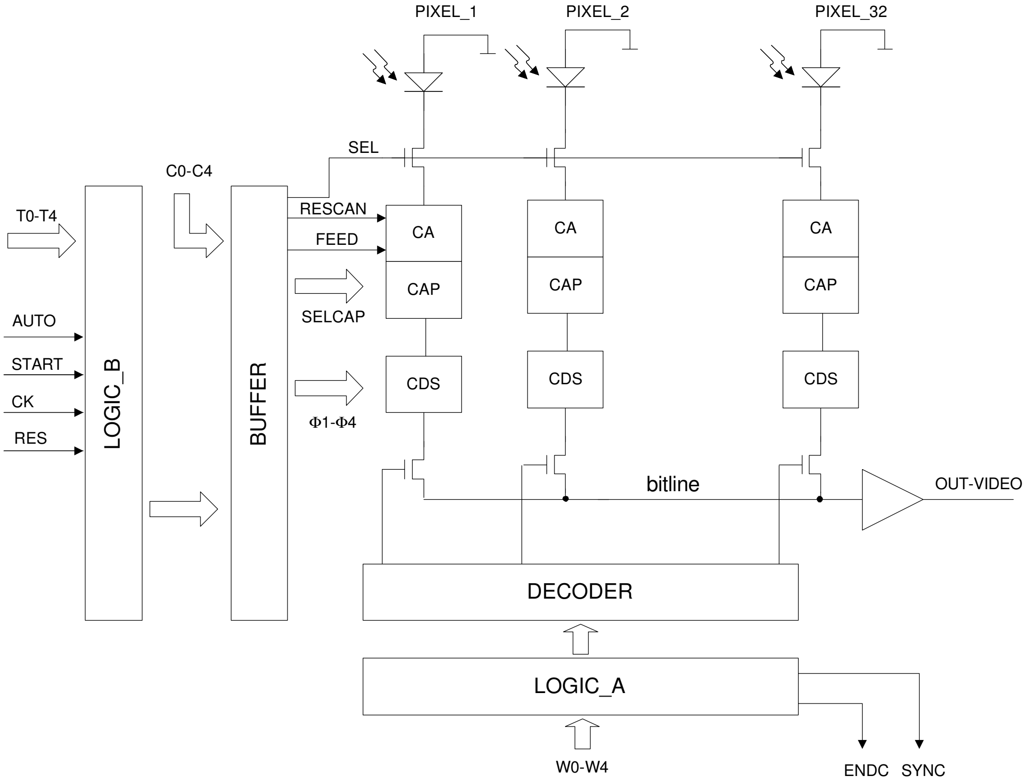


Figure 4 Block diagram of the 32 pixel prototype array

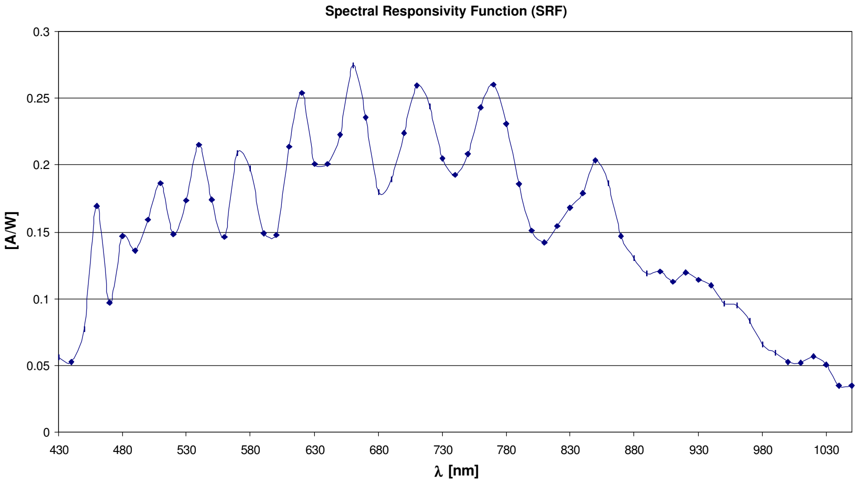


Figure 5 Spectral responsivity of the photoelements

The spectral responsivity, obtained by measuring the response of the photoelements to a normal impinging beam with varying wavelength is in agreement with data reported in literature [23]. Its maximum value of ~0.25 A/W is found around λ~660nm. The several peaks in the curve are due to multiple reflection of light passing through the oxide layers on top of the photosensitive area. The power responsivity has been measured by illuminating the whole array with a white light source and measuring the pixel response as the light power is increased. As expected the curve can be divided into three main regions: a far left region dominated by photoelement noise, a central region where the photoelement response is linear with the impinging power and a saturation region. The values of the slope, linearity and dynamic range of the central region have been calculated for three chips and are shown in Table 1.

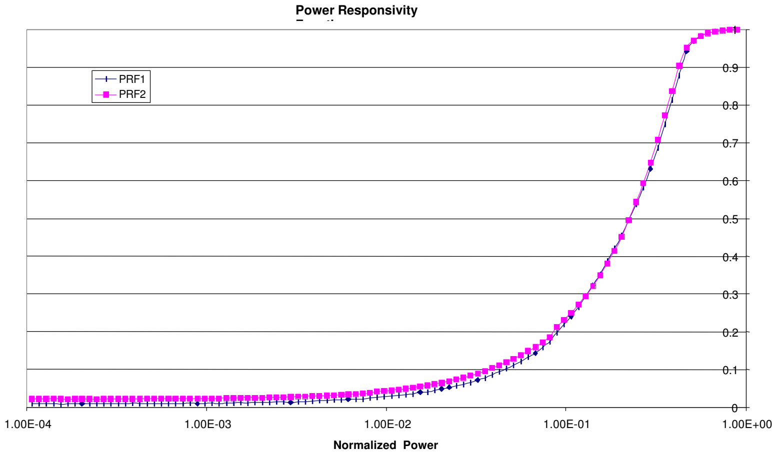


Figure 6 Normalized power responsivity measured on two different samples.

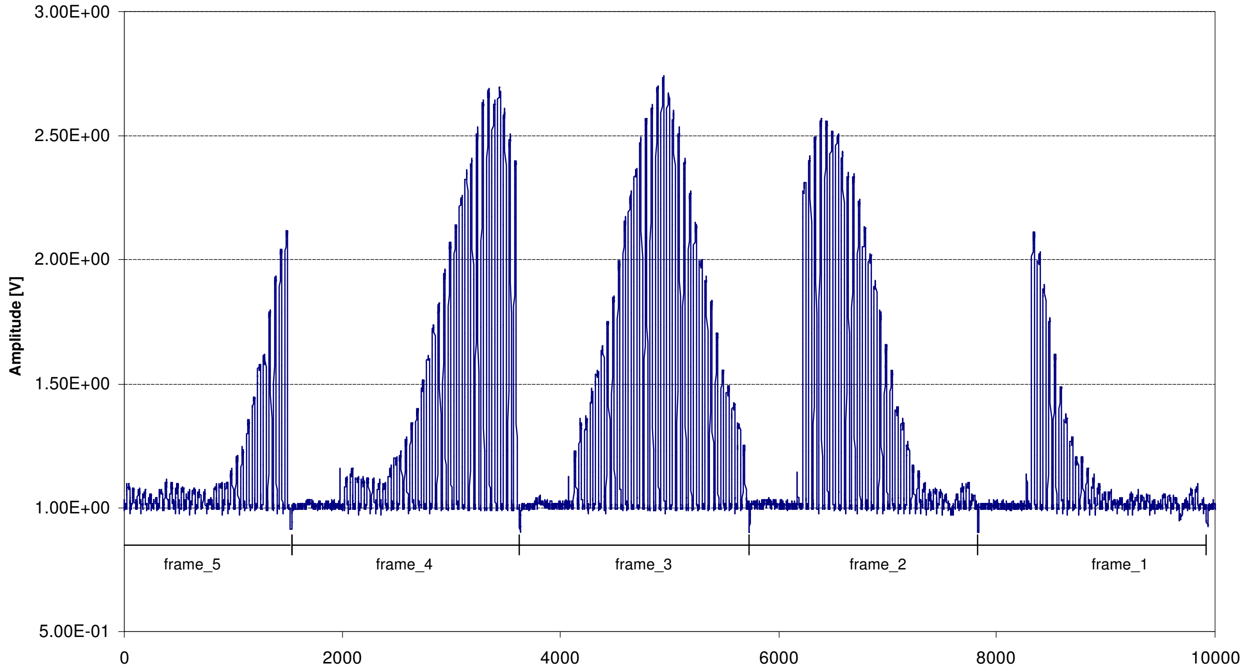
The capability of the sensor of detecting the spot position has been measured by scanning a focused laser spot over the array at different speeds. Figure 7 illustrates the response of the sensor for a scanning speed of 12m/s and a spot diameter of 1.8mm. The sensor was operated in free running mode with an effective frame rate of 34µs. Five successive frames are illustrated showing the spot entering the array from the right side and exiting from the left side.

Table 1 Relevant electro-optical parameters as calculated by power responsivity measurements

Sample #	Power Resp. A/W	Linearity %	Useful Dynamic Range dB
2	0.167	2.9	47
3	0.176	2.9	45
4	0.177	2.8	50

CONCLUSIONS

The results obtained so far have shown that optical sensors have reached a high level of development and reliability that are suited for high accuracy 3D vision systems. The availability of standard fabrication technologies and the acquired know-how in the design techniques, allow the implementation of optical sensors that are application specific: Opto-ASICs. The trend shows that the use of the low cost CMOS technology leads competitive optical sensors. Furthermore post-processing modules, as for example anti reflecting coating film deposition and RGB filter deposition to enhance sensitivity and for colour sensing, are at the final certification stage and will soon be available in standard fabrication technologies.



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