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Integrated optical sensor for 3D vision systems

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ABSTRACT

ACTIVE THREE-DIMENSIONAL VISION IS CONCERNED WITH EXTRACTING INFORMATION FROM THE GEOMETRY AND THE TEXTURE OF THE VISIBLE SURFACES IN A SCENE, REASONING ABOUT THE DATA AND FINALLY, COMMUNICATING THE RESULTS. RECENT ADVANCES IN MICROELECTRONIC TECHNOLOGIES AND INTENSIVE RESEARCH ON INTEGRATED OPTICAL SENSORS HAVE OPENED THE WAY THE REALISATION OF COMPLEX ACTIVE RANGE CAMERA SYSTEMS. THIS PAPER WILL PRESENT THE EFFORT ON THE DESIGN AND DEVELOPMENT OF INTEGRATED CMOS OPTICAL SENSORS FOR ACTIVE THREE-DIMENSIONAL SYSTEMS BASED ON THE OPTICAL TRIANGULATION PRINCIPLE, CARRIED OUT AT ITC-IRST, IN COLLABORATION WITH THE NATIONAL RESEARCH COUNCIL OF CANADA (NRC).

1. Introduction

The desire to capture shape by optical means dates back to the beginning of photography. In the 1860's François Villème invented a process known as photo sculpture, which used 24 cameras [1]. After a few years, however, as it was realised that the photo sculpture technique still needed a lot of human intervention, the idea was abandoned. It is only with the advent of computers that the process of capturing shape by optical means has regained substantial interest, more than 100 years later.

In the last twenty years many advances have been made in the field of solid-state electronics, photonics, computer vision and computer graphics which have allowed the development of compact, reliable and high accuracy 3D vision systems [2,3]. In particular advances in VLSI technology and integrated sensor's development help to accelerate the deployment of 3D vision systems in many fields like visual communication, industrial automation and cultural heritage preservation. This latter field is one of the most stimulating as museum objects, paintings, archaeological site features, architectural elements and sculpture can be digitised to provide a high-resolution 3D digital record of the object or site. The digital record or "digital model" should provide archival quality documentation which can be used for a variety of research, conservation, archaeological and architectural applications, for fabricating accurate replicas as well as for interactive museum displays and Virtual 3D Theatre applications.

Figure 1 summarises all the known optical techniques that can be used to register three-dimensional images. Depending on the measuring range, and on the required accuracy, some techniques may have advantages with respect to others. The classification between active and passive techniques is due to the use or not of light sources helping the registration process. In our work we are mainly working with active techniques which use coherent light sources like collimated laser or laser diode. As a rule of thumb long range applications (>5m) are better satisfied by time-of-flight (TOF) techniques, while triangulation is better for shorter ranges (5mm-5m). Within these latter, the development of integrated sensors for scanned single spot projection systems is the subject of the work we present here.

The next section describes briefly the measuring principle of a state of the art triangulator used to acquire depth maps with depth accuracy as high as 10mm over a depth of field of several centimetres. Section 3 deals with the description of the novel sensor we are proposing and whose actual development stage is illustrated in Section 4. Conclusions follow in section 5.

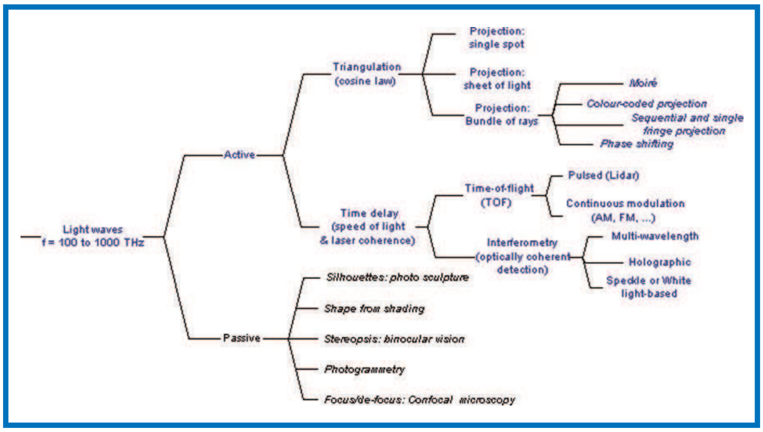

Figure 1. *Main optical techniques for 3D image registering*

2. THE MEASURING PRINCIPLE

A 3D surface map is captured by scanning a laser spot onto a scene, as shown in Figure 2, collecting the reflected laser light, and finally focusing the beam onto a *linear laser spot sensor*. As the beam scans the scene the spot moves continuously along the sensor, its position depending on the depth map. Geometric and photometric corrections of the raw data give two images in perfect registration: one with *x, y, z* co-ordinates and a second with reflectance data. In the figure the auto-synchronised scanner [2] is depicted schematically. Scanning of the laser beam is accomplished by means of two high precision electromechanical galvanometers each one supporting an appropriate mirror. Notice that the mirrors are used both for projection and collection of the laser spot; this arrangement has the advantage of reducing the field of view and thus increasing the stray light immunity.

A laser beam composed of multiple visible wavelengths might also be used for the purpose of measuring the colour map of a scene (reflectance map).

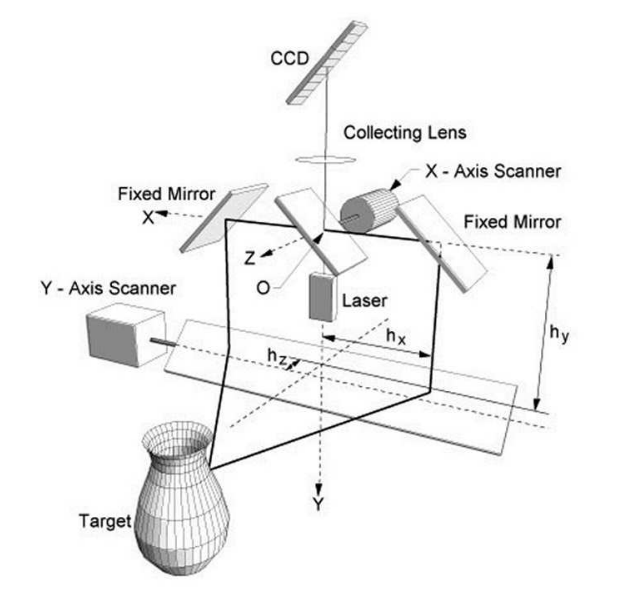

Figure 2. *Schematic diagram of the NRC triangulator based on the auto-synchronised scanning technique.*

3. Proposed sensor

The ITC-IRST and NRC groups are collaborating on a project that is targeted at the integration of key sensors used in the auto-synchronised scanner. These sensors include the *synchronisation photodiodes* based on bicells [4] which control the scanning pattern operated by the galvanometers, and *laser spot position sensors* [5] which detect the position of the spot as a function of the depth map. 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 [6] and multi-resolution random access laser scanners for fast search and tracking of 3D features [7]. 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.

Currently, commercial linear photodiode arrays used in 3D vision sensors are intended for 2D imaging applications, spectroscopic instruments or wavelength division multiplexing in tele-communication 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). Many devices have been built or considered in the past for measuring the position of a laser spot more efficiently. Among those, one finds continuous response position sensitive detectors (CRPSD) and discrete response position sensitive detectors (DRPSD) [9-10]. The category CRPSD includes lateral effect photodiode and geometrically shaped photo-diodes (wedges or segmented). A CRPSD provides the centroid of the light distribution with a very fast response time (in the order of 10 Mhz). DRPSD on the other hand comprise detectors such as Charge Coupled Devices (CCD) and arrays of photodiodes equipped with a multiplexer for sequential reading. They are slower because all the photo-detectors have to be read sequentially prior to the measurement of the location of the peak of the light distribution [7]. Furthermore, consider the situation depicted on Figure 3, a CRPSD would

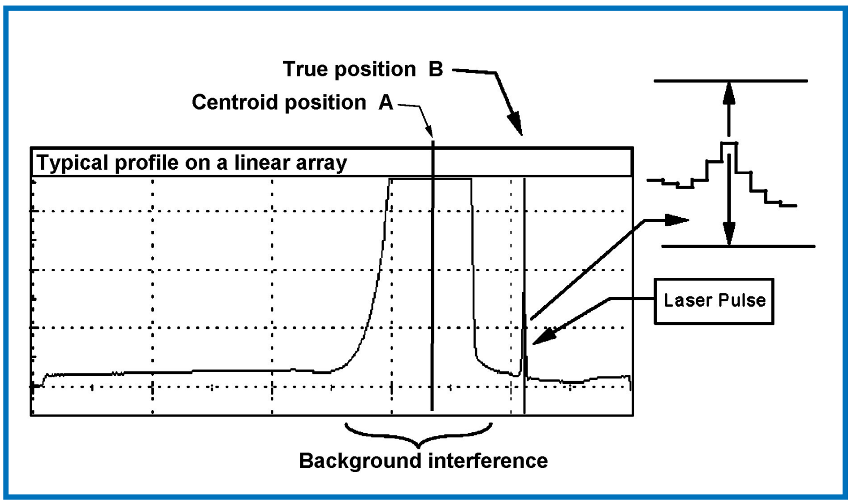

Figure 3. *Typical situation where stray light blurs the measurement of the real but much narrower peak.*

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 [7]. By precision, we mean *measurement uncertainty*. It depends among other things on the signal to noise ratio and the quantization 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. On the other hand, DRPSDs are very accurate because of the knowledge of the distribution but slow. Obviously, not all photo-sensors 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 total array. Hence the new smart detector. Once the pertinent light distribution (after windowing around an estimate around the peak) is available, one can compute the location of the desired peak very accurately.

Figure 4 shows schematically the new smart position sensor for light spot measurement in the context of 3D and colour measurement. In a monochrome range camera, a portion of the reflected radiation upon entering the system is split into two beams (Figure 4.a). One portion is directed to a CRPSD that determines the location of the best window and sends that information to the DRPSD. In order to measure colour information, a different optical element is used to split the returned beam into four components, e.g., a diffractive optical element (Figure 4.b). The white *zero order* component is directed to the DRPSD, while the RGB 1st order components are directed onto three CRPSD which are used for colour detection (Figure 4.c). 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 for each colour with the well-known current ratio method i.e. (I1-

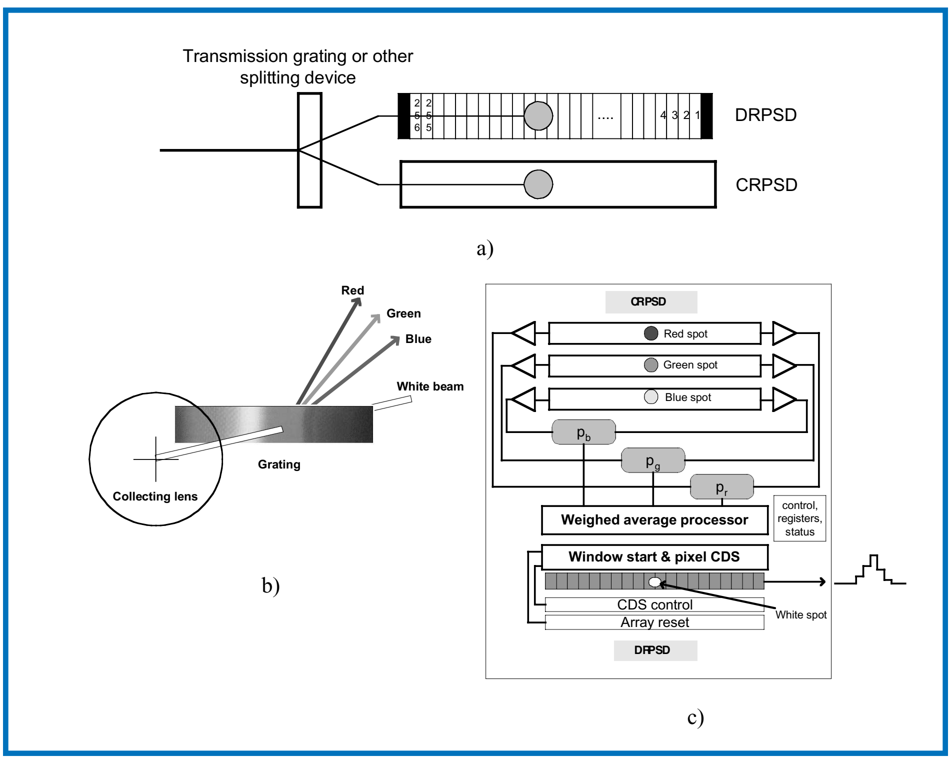

Figure 4. *Description of the smart sensor for laser spot detection: a) in a monochrome system, the incoming beam is split into two components, b) artistic view of a smart sensor with colour capabilities, and c) the proposed sensor.*

I2)/(I1+I2) where I1 and I2 are the currents generated by that type of sensor [4]. The weighed centroid value is fed to a control unit that will select a subset (window) 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 portion of interest.

4. 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 4c. The prototype chip consists of an array of 32 pixels with related readout channels and has been fabricated using a 0.8mm commercial CMOS process. The novelties implemented consist in a variable gain of the readout channels and an automatically selectable readout window of 16 contiguous pixels. Both features are necessary to comply with the requirements of 3D single laser spot sensors, i.e., a linear dynamic range of at least 12 bits and a high 3D data throughput. 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. A diagram of the chip's architecture is shown in Figure 5a. The array pitch is 50mm with each pixel having a sensitive area of 48 x 500 mm^2. The large dimensions of the pixel are required, on one side to cope with speckle noise [6] 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 correlat-

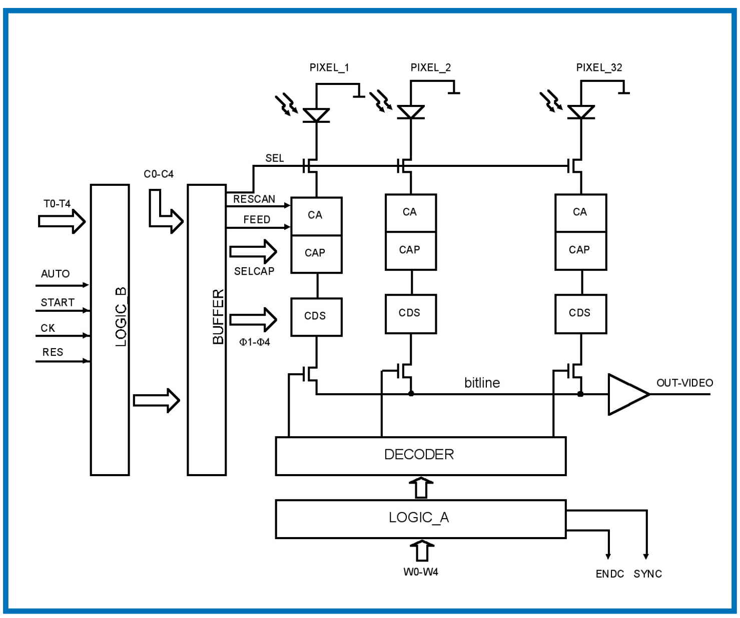

Figure 5. *Schematic diagram of the chip's architecture*

ed double sampling circuit (CDS). To span 12 bits of dynamic range, the integrating capacitor can assume five different values (CAP). In the prototype chip, the proper integrating capacitor value is externally selected. In the final sensor, however, the proper 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 10ms. Within this time the CRPSDs and an external processing unit estimate both the spot position and its total intensity and as calculated by the CRPSDs.

After that, 16 contiguous pixels, as addressed by the window selection logic, are read out in 52ms, for a total frame rate of 64ms. Future sensors will operate at full speed, i.e. an order of magnitude faster. The chip has been tested and its functionality proven to be in agreement with specifications.

Figure 6 illustrates the functionality of the array as a laser spot is scanned on it. The scanning direction goes from right to left and progressive frames are read out from the sensor. The figure shows how the spot moves along the sensor and the good quality of the peak shape reproduction.

5. Conclusions

The results obtained in this work show the feasibility of integrated custom optical sensors,Opto-ASICs, for complex applications like active 3D range cameras. The novel architecture of the linear sensor array proposed, when compared with the linear arrays currently used for such applications, introduces important improvements like fast readout through sub-windowing and high dynamic range (12 bits). Future developments concern the integration on chip of the DRPSD and the detection of colours.

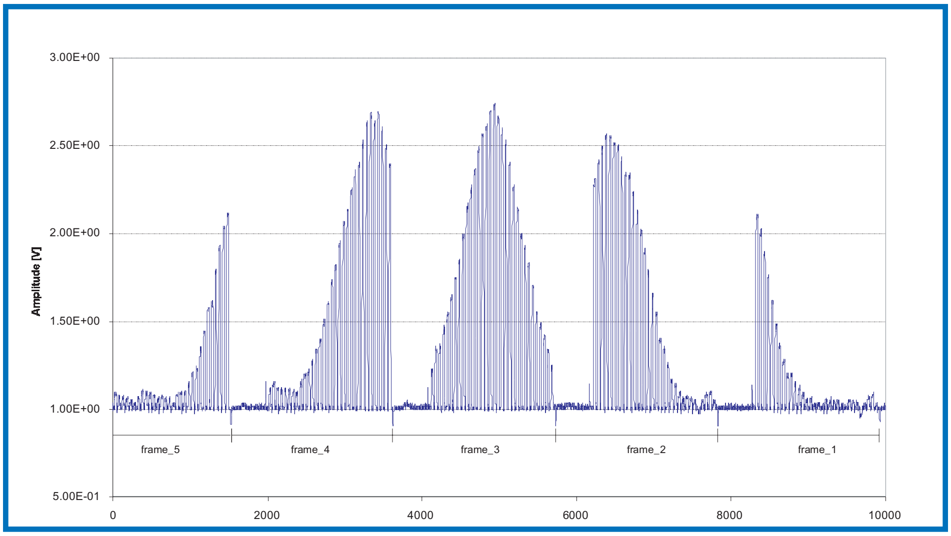

Figure 6. *Multi frame diagram of the chip response as a laser spot is scanner on the photosensitive area.*

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