CMOS image sensors for measuring applications

Tsvetomir Nikolov Lazarov and Todor Stoianov Djamiykov

Abstract – **Current paper presents the structure and main parameters of the modern solid state CMOS image sensors. Increasing complexity of these devices leads to implementation of on-chip image processing by embedded hardware modules and functions. High degree of programming, configuration and communication is available through high-speed interfaces.**

Key words – **CMOS image sensors, parameters, embedded functions, image processing.**

I. Introduction

The modern image sensors are complex, high technology devices, product of the best achievements reached in optics and microelectronics, analog and digital electronic, processors, programming and algorithms.

The image sensor is device that transforms the light into a form convenient for machine processing. Its main task is to encode the information, contained into the light flux in equivalent numbers, which represent the values of the light parameters. There are some requirements – extracted information should be as much as possible, but without unduly increase of its volume; the image sensor itself should add minimal distortions and errors in the final result and should be resistant to different disturbance factors – light and electromagnetic interference, vibrations, temperature.

There are two basic types of solid state image sensors – CCD (charge-coupled device) and CMOS. The basic differences between them are the applied semiconductor manufacturing technology and the way the generated electrons are extracted from every pixel. In the recent years the usage of CMOS sensors in various devices is prevailing. Their electrical parameters (noise, sensitivity, dynamic range) are not better than the CCD's ones, but they are getting closer. Along with their other advantages, CMOS are preferred in most of the current designs and applications. Their main distinctive features include:

- Every pixel is in fact a "active cell" – it not only transforms the light to photo-electrons, but also makes charge to voltage conversion and local gain;
- Pixels are individually addressed;
- Embedded analog-to-digital conversion;
- Embedded analog and digital signal processing applied to the individual pixels and/or to the whole image;
- Embedded hardware of a microcontroller system – processor, program and data memories, special function registers, communication interfaces;
- Programmable control parameters and variables, operation mode selection, configurable image processing functions and output data format;
- Embedded voltage regulator, PLL, digital-to-analog converter, test pattern generator and so on.

All the features, listed above, implemented into a single chip define a higher class electronic device – System-on-Chip (SoC). In case of image processing device, another term is also used – Camera Chip.

II. Sensor structure

Simplified vertical structure of image sensor is presented on fig.1. The basic building block is the light sensitive element – as such is used a photo diode. The light penetrates into the depth of the diode and generates photoelectrons which are stored during the exposition. Then they are converted to voltage that is additionally gained and converted to digital code. The code represents the amount of light descent onto the surface of the photo diode. Many diodes are arranged in a two dimensional array in order to achieve spatial resolution of the image projected over the sensor. Every diode generates such amount of electrons that is proportional to the light incident on its surface. As final result, the image sensor outputs a sequence of numbers that represent the spatial distribution of the light falling over the entire photo sensitive array of the sensor.

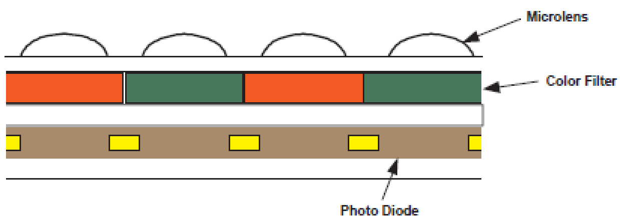

Figure 1. Simplified structure of image sensor

The light is electro-magnetic radiation with a wide spectrum and the length of the electro-magnetic wave could be parameter containing information. Separation of the colors contained in the light flux is by color filters

T. Lazarov is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria,
e-mail: tsvetomirlazarov@yahoo.com
T. Djamiykov is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: tsd@tu-sofia.bg

transparent for the light with wave length from certain diapason. Most of the modern image sensors use Bayer matrix pattern arrangement of the color filters.

There is additional layer of optic elements – microlens, placed above the color filters in order to increase the percentage of accepted and converted light and to reduce the parasitic interference between the neighbor pixels. The microlenses focus the light and direct it toward the photo sensitive part of the pixel.

The extraction of the signal generated from the pixels applies method specific for CMOS sensors. There are two lines – row addressing line and column signal line. The rows are addressed is sequence one by one. When a certain row is activated, every pixel from this row is connected to its column signal line. There is a local analog amplifier at the end of the column line. Pixel signal is stored in the capacitor of a sample-and-hold (S/H) after the amplifier. The columns are addressed is sequence one by one and the voltages from S/H are multiplexed to analog-to-digital convertor. In many sensors there are individual ADC at every column for reducing the processing time of the frame.

Analog processing provides analog gain of the signal form the individual pixels and eliminates the offset. Analog gain is individually programmable for the different colors. A special type of pixels “black pixels” are used for noise reduction. They are isolated from the falling light and do not generate photo electrons. Their signal is “dark current” caused by temperature and technology inadequate. Analog processing includes also analog-to-digital conversion.

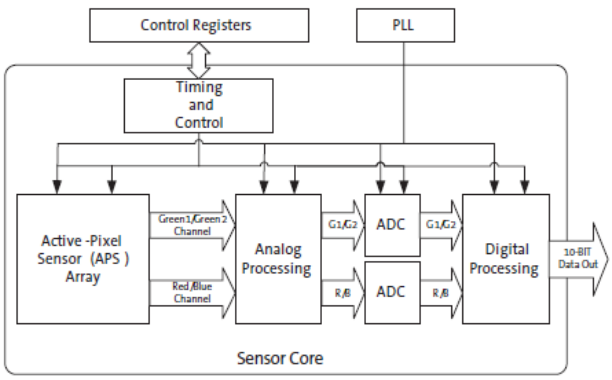

Figure 2. Sensor Core Block Diagram

Digital processing makes additional digital gain and offset correction, defect pixel correction, compensation of distortions added by the system optic, contrast and gamma correction, converts color coding from RGB to YUV and reverse and a lot more described later in this paper.

All processes are synchronized and timed by clock and control signals generated by Timing Generator. Time variables, gain coefficients, are set by writing adequate values into the corresponding control registers. Activation of certain image processing functions and setting their parameters is done through other special function registers.

Figure 3 presents block diagram of Camera Chip. Besides the Sensor Core, the other components of the system include Processor and its memories (RAM and ROM), Image Flow Processor, Output Interface and PLL.

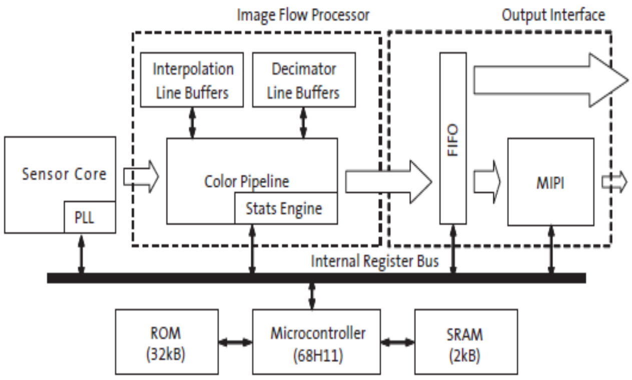

Figure 3. System-on-Chip (Camera Chip) Block Diagram

The processor could be a microcontroller, DPS, or a dedicated hardware module, optimized for a certain task or application. Processor’s program memory ROM contains main program and drivers for the different functional subsystems. The users have access to some registers placed into the RAM through user communication interface.

Image Flow Processor executes most of the image processing functions applied to the frame. Their activation and parameters are selected by the user. Some functions require more information during the calculation of the current pixel’s value. The values of the neighboring pixels, including those from the previous and the next rows are needed. They are stored in the buffers in the RAM. During the frame processing, a special module Stats Engine calculates statistic information about the frame and at the end this information is loaded into a dedicated registers. The user can access this information through the user communication interface.

Output Interface prepares the digital sequence of pixel values into the required format. Information bits are formatted to meet the requirements of the used physical interface. Two main transformations occur. Data bits are packed into bytes and if serial output interface is used, parallel data bits are serialized. Synchronization is achieved by additional signals and/or bits. Some sensors are capable of producing composite video signal. Data transfer rate depends on the physical interface parameters and the internal clock.

Master clock of the sensor is generated and maintained stable by the embedded PLL module. It is fed by external clock signal provided by the main system clock. In some sensors, there is internal clock generator and only a quartz resonator is needed.

III. FUNCTIONS AND SIGNAL PROCESSING

There are a lot of image processing functions and algorithms embedded into the modern CMOS image sensors. All of them are implemented as tools for getting image with enhanced parameters. They work on different image characteristics and have various impacts to the end result. The following rough classifications could be made.

According to the nature of the signal that is being processed, there are analog processing on voltage signal till analog-to-digital conversion, digital processing – works with digital numbers and output signal formatting. Figure 4 presents this point of view.

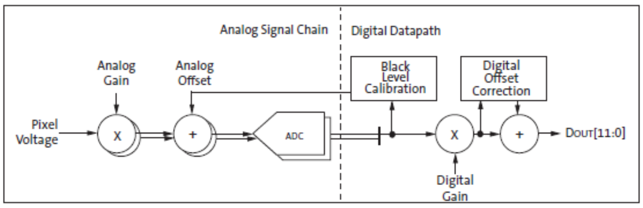

Figure 4. Signal processing flow

Other possible division is functions that control the process of light transformation, image processing functions and user frame formatting. The latter group includes output data format selection, Horizontal Mirror, Vertical Flip, Column and Row Skip and Binning, Window Size and Position, Image Cropping and Scaling.

Most of the functions that control the transformation of the light to digital code are automatic but there are also options for parameter setting and/or direct user control. Examples of this type of functions are Exposure Control, White Balance, Band Filter, Flicker Detection, Detection and Black Level Calibration, 50/60Hz Luminance.

The functions for image quality control color saturation, hue, gamma, sharpness (edge enhancement). Distortions caused by the system optics could be compensated by Lens Correction function, which have available zone and correction coefficient settings. Other standard image processing functions are Digital Gain, Defect Pixel Correction and Noise Reduction, Contrast and Gamma Correction, Color Interpolation and Edge Detection, RGB to YUV Conversion, Color Kill.

Besides the functions that transform the main information flow, there is a set of additional functions – low-power mode (Standby, Shutdown) activation, external actuators (mechanical shutter, light source, system optic) control, generation of predefined test frames (Test Pattern Generator). Output data format implements pixels bits packaging and serialization, generation of synchronization signals and protocol specific functions. Two-wire I2C-compatible interface and protocol for data transfer is used as a user communication interface. Some sensors have additional four-wire SPI interface.

IV. IMAGE SENSOR PARAMETERS

Table 1 contains main parameters of representative CMOS image sensors, manufactured by Aptina Imaging Corporation and OmniVision Technology, Inc.

The very first parameter that is presented to the user is the resolution – total number of picture elements available to the user. It is the product of multiplication of number of rows by the number of columns and its dimension is MP (Mega Pixels). Mass produced sensors have about 0,5-10MP. Resolution defines frame format and frame transfer rate. It is often practice to use not the entire amount of available pixels, but the closest video graphical format.

The pixels usually have a square shape but this not obligatory. The length of the side have a typical value 1,4-5,6μm. It determines its sensitivity, dynamic diapason signal/noise ration. When the size of the pixel decreases, these parameters also get lower value. The other consideration, opposing to the previous one, is the spatial resolution – smaller pixels are needed in order to distinguish finer image elements.

Sensor resolution and the size of the pixel determine dimensions of the photo sensitive area on which the image is projected by the system optic and hence its optical format.

Embedded analog-to-digital convertor has 8-12 bits resolution. In some applications, least significant bits are discarded during the output data formatting when higher frame rate is required and/or low resolution is suitable.

External clock frequency is about 5-55MHz. It is increased up to 80MHz and stabilized by the internal PLL module. If the PLL is deactivated in order to decrease the power consumption, internal Master clock works with half of the external clock frequency.

Frame rate depends on the internal clock frequency, frame format (amount of pixels transferred) and output data format (serial or parallel, compressed) and output interface parameters.

The voltage of the power supply for the sensor's subsystems is separated as follows: 1,2V-1,8V to digital, 2,8V or 3,3V to analog part, 1,7V-3,3V for I/O buffers and 2,5V-3,3V for PLL. Total consumption depends on the working mode (active or low-power), clock frequency and the frame format. It is about 250-400mW in active mode and could be reduced to 10-70μW in power-save mode.

CMOS sensors in higher class have significantly enhanced parameters. They have 10-16MP, 14/16-bit ADC, high speed serial interfaces for frame transfer. They are capable of maintaining 30/60fps frame rate at full resolution and considerable frame rate at lower frame formats.

TABLE 1. PARAMETERS OF CMOS IMAGE SENSORS

Device: / Parameter:		**MT9M012**	**OV10633**	**MT9D112**	**OV3640**	**MT9T031**	**OV3640**	**MT9P006**	**OV5650**	**MT9J003**	**OV10810**	**MT9H004**	**OV16820**
Resolution, MP		1,6	1	2	2	3	3,1	5	5	10	10	16	16
Active array	H	1472	1280	1600	1920	2048	2048	2592	2592	3856	4320	4928	4608
	V	1096	720	1200	1080	1536	1536	1944	1944	2764	2432	3280	3456
Pixel size, µm		2,2	4,2	2,2	3	3,2	1,75	2,2	1,75	1,67	1,4	4,78	1,34
Image area, mm	H	3,24	5,51	3,56	5,86	6,55	3,63	5,70	4,59	6,12	6,09	23,55	6,24
	V	2,41	3,42	2,68	3,28	4,92	2,71	4,28	3,42	4,59	3,45	15,68	4,68
Optical format, inch		1/4,5	1/3	1/4	1/2,7	1/2	1/4	1/2,5	1/3,2	1/2,3	1/2,5	1,77	1/2,3
ADC, bits		12	10	10	10	10	10	12	10	12	12	14	12
Dynamic range, dB		70,1	115	59,5	69	>61	60	76	69	65,2	71		
SNR, dB		38,1	39	37,7	39		36		37		35		
Sensitivity, V/lux-sec		1,4	3,65	0,53	3,3	>1	0,49	1,76	1,3	0,31	0,72		
Input clock, MHz		49,5	6-27	6-54	6-27	48	6-54	96	6-27	6-48	6-27	46,4	6-27
Max. frame rate, fps													
Full resolution		30	30	15	30	12	15	15	15	15	30	10,48	30
Video mode		60		30	60	43	30	60	30/60		30/60	60	30/60
Max. data rate, Mb/s					800					2800		2592	
	MP/s	99		40		48		96		80			
Data output:	Parallel	12	10	10	10	10	10	12	10	12	12		12
	MIPI			x1	x1		x2		x2	x4	x8		x8
	LVDS										x8	x8	x8
Supply Voltage, V	I/O	2,6-3,1	1,7-3,6	1,7-3,1	1,7-3,6	3,3	1,7-3,0	1,7-3,1	1,8/2,8	1,8/2,8	1,7-3,0	3,3	2,8/1,8
	Analog	2,8	3,3	2,8	3,3	3,3	2,8	2,8	2,8	2,8	2,8	3,3	2,8
	Digital	1,8		1,8	1,5	3,3	1,5	1,8	1,5	1,8	1,5	1,8	1,2
Power consumption:	Active, mW	365	532	245	357	244	79	366	150	638	230		310
	Standby, µW		480	10	70	1,65	20		40		40		10

V. CONCLUSION

There is a rich variety of sensors with different configurations of parameters and features. This fact makes possible design and implementation of CMOS image sensors in electronic devices for very wide spectrum of applications.

The choice of sensor for a certain solution depends on the application and the parameters of the task, available resources (processor, memory, power supply) and required image processing algorithms that should be implemented.

SoC sensor has embedded a big portion of the image processing functions. Their adequate utilization could save a lot of resources at system level – design time, hardware, source code (memory). Transfer of the image processing into the sensor allows choice of a simpler processor and/or implementation of higher class algorithms to get better end result.

System designer is freed from technical details and is able to focus on the main tasks – selection of functions to be applied into the SoC with setting the correct parameters and information extraction from the image (high level digital processing of the pixel flow generated by the CMOS sensor).

Direct access to the raw data from ADC is precious feature. The information contained in this data makes it easier to tune and test the entire system that includes the sensor. It also makes possible implementation of signal processing that is not included in the sensor's features list and/or require information extraction from raw data.

ACKNOWLEDGEMENT

This work is supported by the Technical University – Sofia under Contract 122ПД0049-03.

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